SIMULATION AND DESIGN
OF AN AUTOMATIC CONTROLLER
FOR A FAST BREEDER NUCLEAR REACTOR
POWER PLANT

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THESIS

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Simulation and Design of an Automatic Controller for a Fast Breeder Nuclear Reactor Power Plant

by

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ABSTRACT

The dynamic equations for a Liquid Metal Fast Breeder Nuclear Reactor (LMFBR) Power Plant are derived. These non-linear differential equations with typical design values for the system parameters are solved on a COMCOR Ci 5000 analog computer for the characteristic transients of the basic plant and the results compared with a recently proposed LMFBR design. A digital computer automatic control program is developed which uses, in addition to the ideas of derivative and proportional control, precomputed control trajectories. The digital controller design is implemented by applying FORTRAN IV programming to the XDS 9300 digital computer. The effectiveness of the strategy for the automatic controller is demonstrated by using various step changes in the load demand.

A special software routine was written to automatically scale the analog computer and proved to be quite useful in improving the operating efficiency of the hybrid computer simulation.

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I. INTRODUCTION

In view of the enormous increase of world power consumption and the fast decrease of the resources which may be used to satisfy this growing power demand, it became necessary to develop and build nuclear power plants. The reactors used to generated the power for these plants are up to now almost exclusively thermal reactors using uranium as fissionable material. There are 3 fissionable isotopes: U (235), Pu (239), and U (233). U (235) is found in natural uranium and can be used in this state or in an enriched form, i.e., its percentage is increased beyond that in natural uranium. Pu (239) is manufactured by nuclear reaction from U (238). U (233) is similarily manufactored from Th (232), an isotope which is also found in natural uranium.

The worlds supply of nuclear fuel consists of 25×10^6 tons of natural uranium, mostly U (238), and 1×10^6 tons of thorium, mostly Th (232) [10]. The natural uranium consists of 99.29% U (238) and 0.71% U (235). Since U (235) is the only naturally fissionable isotope the use of nuclear fuels would be limited to 0.71% of 25×10^6 tons. This means that, using only the present thermal type reactors with their inefficient nuclear economy a shortage of nuclear fuel is lightly to occur by the year 2000.

An increased nuclear economy in an uranium reactor can be achieved by using fuel breeding. In this process the nonfission

capture of neutrons by a fertile U (238) nucleus results in the generation of fissionable Pu (239). Fertile Th (232) can also be converted to fissionable U (233). If more fissionable nuclei are produced than are consumed the reactor in which this process takes place is called a Breeder Reactor. If the fission process depends on fast neutrons as in the above described processes the reactor is a Fast Breeder Reactor (FBR).

The control Problem of a FBR is particularly acute because of two important facts. First of all due to the high energies required of the neutrons in order to produce fission, the power per unit volume is much larger than in the presently used thermal type reactors [10]. The high power density results in steep temperature gradients, large coolant temperature rises and therefore coolant distribution problems.

The second important fact is the lack of inherent load following capability of this type of plant [2]. This is due to the fact that the load fluctuations do not feedback as efficiently through the coolant medium as they do in thermal type reactors. For these reasons constant automatic supervision and control of a fast breeder reactor is necessary.

To design a controller for a nuclear power plant it is necessary first to obtain a mathematical model. In this report, the dynamic equation of a LMFBR are derived. The next step in the design procedure was to determine the dynamic behavior of the complete plant following selected changes in both the controlling inputs (reactivity, valve opening) and in the load. Because of the nonlinearity of the system, model simulation was required in order to obtain a solution for the dynamic

response. From this simulation conclusions were drawn about the characteristics which the controller must have and about the required control strategy.

The real-time solution of the dynamic equations is performed by the analog computer (COMCOR Ci 5000) in a hybrid linkage with the digital computer (XDS 9300).

The controller design developed in this report uses the digital computer as the controlling element. The economic advantage of using a digital controller results from the prospect of operating a general purpose type computer in the time-share mode to perform both the control decisions as well as the monitoring data processing and such other related functions that are presently being performed by such digital computers.

A digital computer automatic control program is then developed on the basis of the results of the simulated plant response. The design strategy includes in addition to the ideas of derivative and proportional control, precomputed control trajectories. The digital controller design was implemented by applying FORTRAN IV programming to the XDS 9300 digital computer. The effectiveness of the strategy for the automatic controller is demonstrated by using various step changes in the load demand.

A special software routine was written to automatically scale the analog computer and proved to be quite useful in improving the operating efficiency of the hybrid computer simulation.

II. PLANT DESCRIPTION

The plant considered in this investigation consists of:

1) Fast Breeder Nuclear reactor with control rods
2) Primary sodium coolant loop
3) Heat exchanger (counterflow)
4) Secondary sodium coolant loop bypass and bypass control valve
5) Steam generator
6) Steam loop with turbine and condensor

Additional components which are found in nuclear reactor power plants such as pumps, intermediate heat exchangers, pressure tanks, equalizer tanks, storage tanks, reheater, superheater, and intermediate turbine stages, were not included since they would not have served the purpose of this investigation. By adding these parts, the basic structure of the system would not be changed and would still be valid.

A flow diagram of the plant is given below.

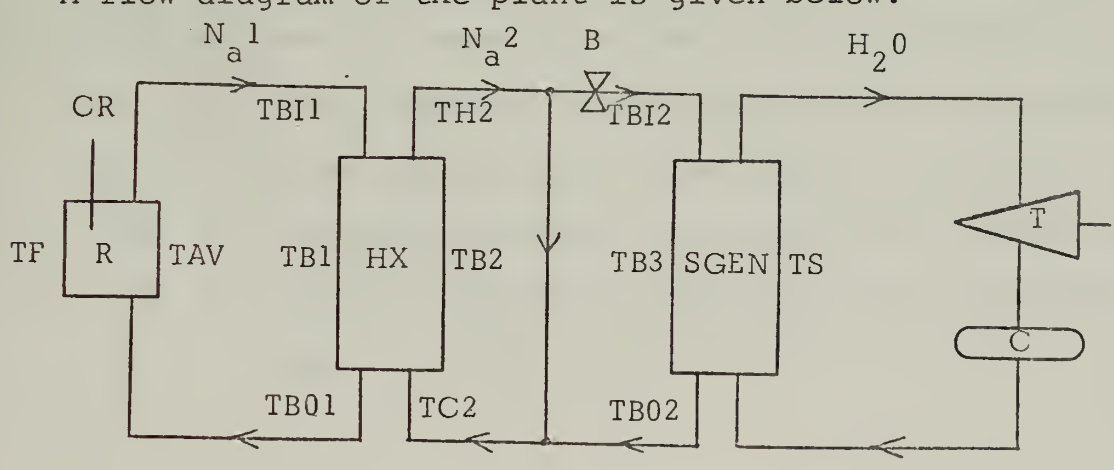


Fig. 1. Plant flow diagram.

R = Fast Breeder nuclear reactor

CR = Control rods

HX = Heat exchanger

SGen = Steam generator

T = Turbine

C = Condenser

Na1 = Primary sodium loop

Na2 = Secondary sodium loop

H_2O = Steam circuit

B = Sodium bypass valve

TF = Average fuel temperature

TAV = Average coolant temperature in reactor core

TC1 = Reactor inlet temperature

TH1 = Reactor outlet temperature

TBI1 = Inlet temperature heat exchanger primary side

TBO1 = Outlet temperature heat exchanger primary side

TB1 = Average temperature heat exchanger primary side

TH2 = Outlet temperature heat exchanger secondary side

TC2 = Inlet temperature heat exchanger secondary side

TB2 = Average temperature heat exchanger secondary side

TBI2 = Inlet temperature steam generator primary side

TB02 = Outlet temperature steam generator primary side

TB3 = Average temperature steam generator primary side

TS = Average temperature steam generator secondary side

III. MATHEMATICAL MODEL - PLANT DYNAMICS

A. REACTOR CORE

1. Neutron Kinetics

The neutron kinetic equation with one group approximation [1] is given as

$$\frac{dn(t)}{dt} = \frac{\partial K(t)-\beta}{\ell} n(t) + \lambda c(t) \qquad \text{(III.1)}$$

$$\frac{dc(t)}{dt} = \frac{\beta}{\ell} n(t) - \lambda c(t) \qquad \text{(III.2)}$$

where $n(t)$ = neutron density

$\delta K(t)$ = reactivity

β = fraction of delayed neutrons

ℓ = neutron lifetime

λ = average decay constant

$c(t)$ = average concentration of delayed neutrons

The steady state conditions are given by

$$\delta k(t) = 0$$

$$\frac{\beta}{e} n_o = \lambda c_o$$

where n_o = steady state neutron density

c_o = average steady state concentration of delayed neutrons

When setting

$$\frac{\delta K(t)}{\beta} = K(t)$$

$$= \text{reactivity in dollar units}$$

$$\frac{n(t)}{n_o} = N(t)$$

$$\frac{c(t)}{c_o} = D(t)$$

the following equations are obtained

$$\frac{dN(t)}{dt} = \frac{\beta}{\ell} (K(t)\ N(t) - N(t) + D(t) \tag{III.3}$$

$$\frac{dD(t)}{dt} = \lambda\ (N(t) - D(t)) \tag{III.4}$$

The numerical values for a fast reactor for β and ℓ are approximately given as

$$\beta \cong 3 \cdot 10^{-3}$$

$$\ell \cong 6 \cdot 10^{-7}$$

Therefore $\frac{\beta}{\ell} \simeq .5 \cdot 10^{4}$

If the differential equation for N(t) is brought into the form

$$0 = K(t)\ N(t) - N(t) + D(t) - \frac{\ell}{\beta}\frac{dN(t)}{dt}$$

The last term, being small compared to the other three terms may be neglected. Using this approximation the equation for the neutron kinetics in the reactor core are then given as

$$\frac{dD(t)}{dt} = \lambda\ (N(t) - D(t)) \tag{III.5}$$

$$N(t) = \frac{D(t)}{1-K(t)} \tag{III.6}$$

with the steady state, initial conditions

$$N(0) = D(0) = 1 \tag{III.7}$$

2. Reactivity Coefficients

In addition to the controlled reactivity input applied by positioning of the control rods, a nuclear reactor has inherent reactivity feedback, produced by thermohydraulic effects. The total reactivity is given as

$$K_T(t) = K_R(t) + K_F(t) \tag{III.8}$$

where $K_R(t)$ = controlled reactivity input

$K_F(t)$ = inherent reactivity feedback coefficients

In a fast reactor the following reactivity coefficients are of importance

a) Doppler coefficient

b) Fuel axial expansion coefficient

c) Fuel radial expansion coefficient

d) Clad temperature coefficient

e) Sodium temperature coefficient

a block diagram for the stability model is given in Fig. 2.

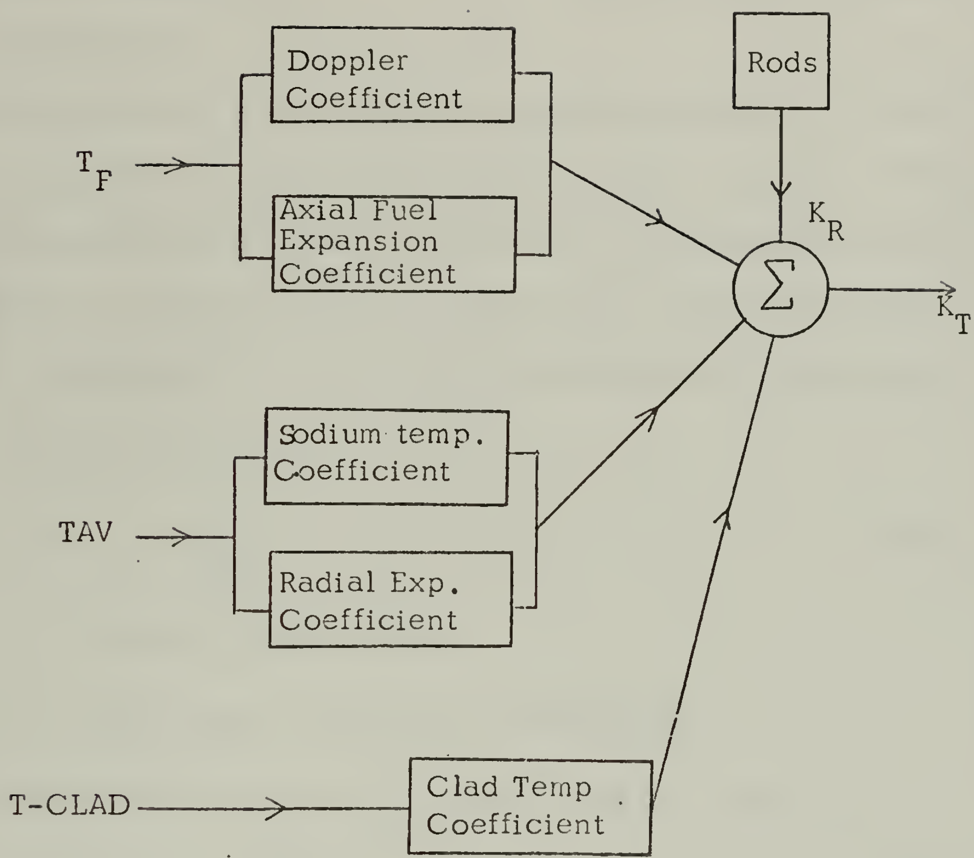


Fig. 2. Block Diagram for reactivity feed back paths.

The numerical values of the reactivity coefficients are given as [2]

a) Doppler coefficient − 1.39 cents/ % power

b) Fuel axial expansions coefficient − .32 cents/ % power

c) Clad temperature coefficient + .0138 cents/ % power

d) Sodium temperature coefficient + .0057 cents/ % power

e) Radial expansion coefficient - .0043 cents/ % power

From the above data it is seen that coefficients c, d, and e are several orders of magnitude smaller than a and b. Therefore, these reactivity coefficients will be neglected and it will be shown in section IV that this does not lead to any noticeable inaccuracy. The reactivity feedback coefficient may now be expressed as

$$K_F = K_D + K_{EXP} \qquad \text{(III.9)}$$

where K_D = doppler coefficient

K_{EXP} = fuel axial expansion coefficient

and the equation for the total reactivity is given as

$$K_T = K_R + K_D + K_{EXP} \qquad \text{(III.10)}$$

If the numerical values for the reactivity coefficients are introduced along with the dollar units of reactivity (see Appendix A), the final equation for the reactivity feedback is given as

$$K_T = K_R - .0014\ TF \qquad \text{(III.11)}$$

with the control block diagram given in Fig. 3.

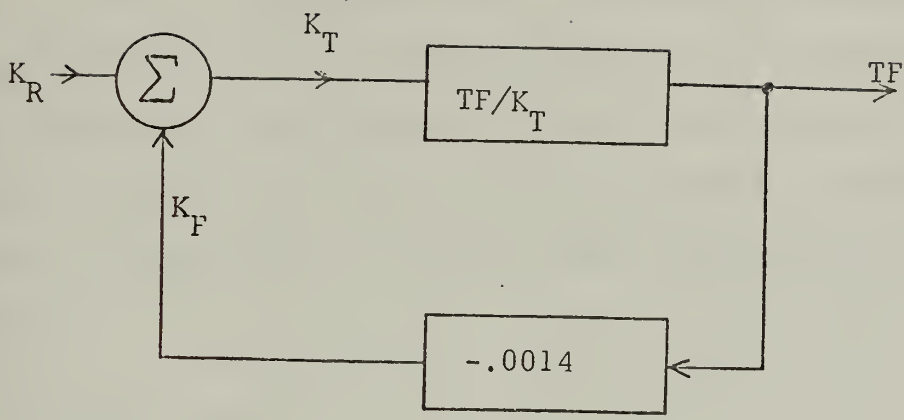


Fig. 3. Reactivity Feedback Model (Simplified).

3. <u>Heat Generation</u>

The rate of heat produced per unit volume of fuel is called the volumetric thermal source strength Q_N and is given by [4]

$$Q_N = G \cdot n(t) \cdot \sigma_f \cdot \phi \tag{III.12}$$

where G = energy per fission, Mev

$n(t)$ = number of fissionable fuel nuclei/cm^3

σ_f = Microscopic fission cross section of the fuel

ϕ = neutron flux per cm^2 sec.

If n is taken as a constant for a certain fuel element, it is seen from the above relation, that the generated heat is proportional to the product of the fission cross section σ_f

and the neutron flux ϕ. The neutron flux is dependent upon the fissionable species used and the energy of fission neutrons, which in turn, is dependent upon the reactor temperature. If σ_f if determined for a certain reactor, it is seen that the heat generated at any point is directly proportional to the neutron flux at that point, which is directly proportional to the earlier used N(t). The generated heat may therefore be written as

$$Q_N = A\ N(t) \tag{III.13}$$

where A = proportionality factor, which is constant if σ_f is assumed to be a constant

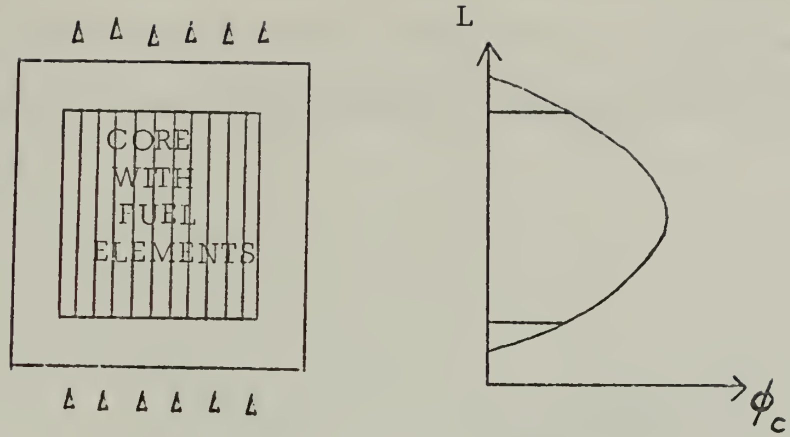
B. HEAT TRANSFER

1. Reactor

a. Fuel to Coolant

The core of a fast nuclear reactor consists of a great number of fuel elements. In a proposed 1 MW Fast Breeder Reactor [2] for example, there are 470 fueld rods, each fuel section (core length) is 2 feet long and the rod has an overall diameter of .25 inches. The fuel is enclosed in a cladding of wall thickness of .015 inches.

Due to the size of the fuel element the radial flux distribution within the core may be neglected. The axial flux distribution is shown in Figure 4.



Coolant

Fig. 4. Reactore Core and Axial Flux Distribution.

If the axial variation in flux is taken into account, it is seen from figure 5 that the generated heat and therefore the temperature in the fuel element, cladding and the coolant varies in the axial direction of the fuel element.

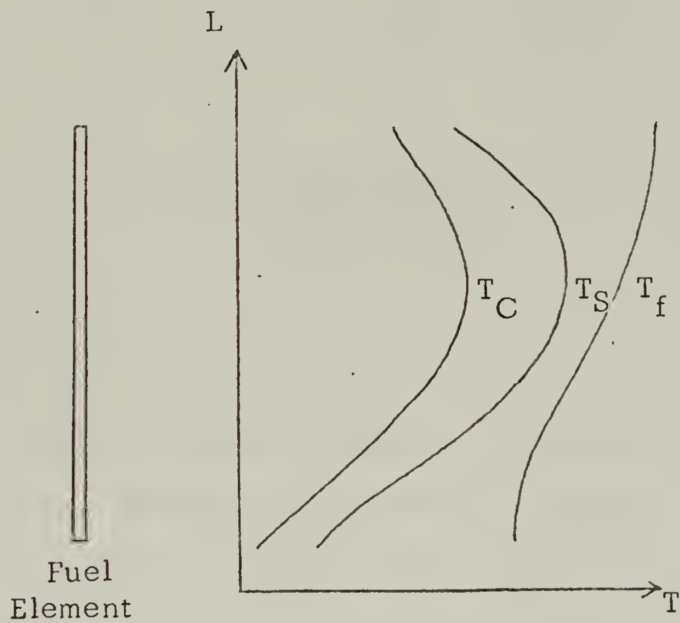


Fig. 5. Temperature variation along fuel element (center, cladding, coolant).

In this investigation, however, since the reactor is only a part of the total power plant, these special effects will be neglected. Only average temperatures will be considered.

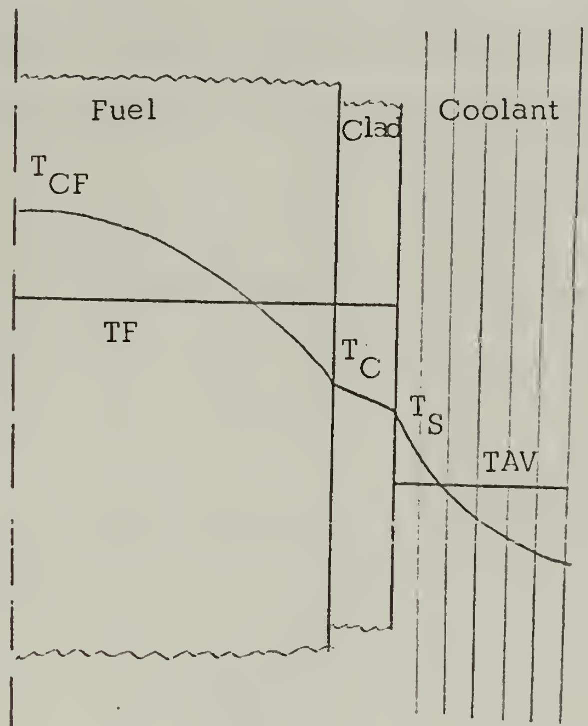


Fig. 6. Temperature profile in fuel element.

Figure 6 shows a typical temperature profile within the fuel element, cladding and coolant together with the average temperature profile considered here. The effect of the cladding is neglected, which is justified in view of the earlier given numerical values. Taking the average temperatures simplifies the mathematical solution without introducing

considerable errors. If more accuracy is desired, the obtained temperature values could always be corrected with a multiplication factor for point values or for optimal accuracy the temperature distribution model may be obtained by the solution of partial differential equations [3].

Under the above assumptions the heat balance for a single fuel element, whose diameter is small with respect to the core, may be written for the steady state heat transfer as:

$$Q_F \, 2\pi r \, dr \, L = Q_{r+dr} - Q_r \tag{III.14}$$

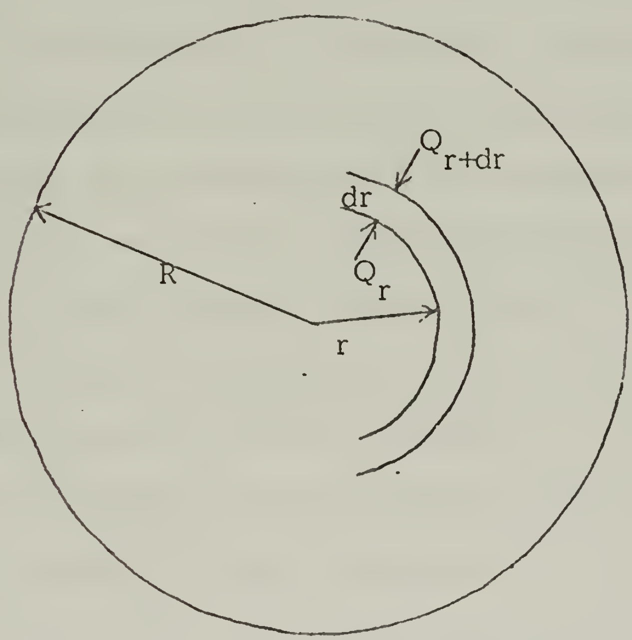


Fig. 7. Cross section of cylindrial fuel element.

The solution to this equation with the boundary condition

$$\left.\frac{dT}{dr}\right|_{r=0} = 0$$

$$\left.T\right|_{r=0} = TF$$

is (see Appendix B)

$$Q_F = K\ A\ (TF - TAV) \tag{III.15}$$

where K = Thermal conductivity, in this case an average value for the fuel cladding and coolant $\left[\frac{\text{cal}}{\text{sec cm}^2\ °\text{C}}\right]$

A = surface area of the fuel element [cm^2]

The thermal conductivity of the fuel and cladding and the physical properties of the coolant (density, viscosity, and specific heat) are considered to be constant and independent of temperature, which is a valid assumption for medium power variations of the reactor. For the above assumptions the product K . A may be considered constant, depending only upon the physical size of the fuel element. For the dynamic case of the heat transfer the heat capacitance of the fuel must be taken into account. Using the analogy of an electric circuit for heat flow, where heat flow is equivalent to current, temperature equivalent to voltage, and heat sink (dissipation) equivalent to a resistor, the following relationship can be written

$$Q_N = C_f \frac{dTF}{dt} + Q_F \tag{III.16}$$

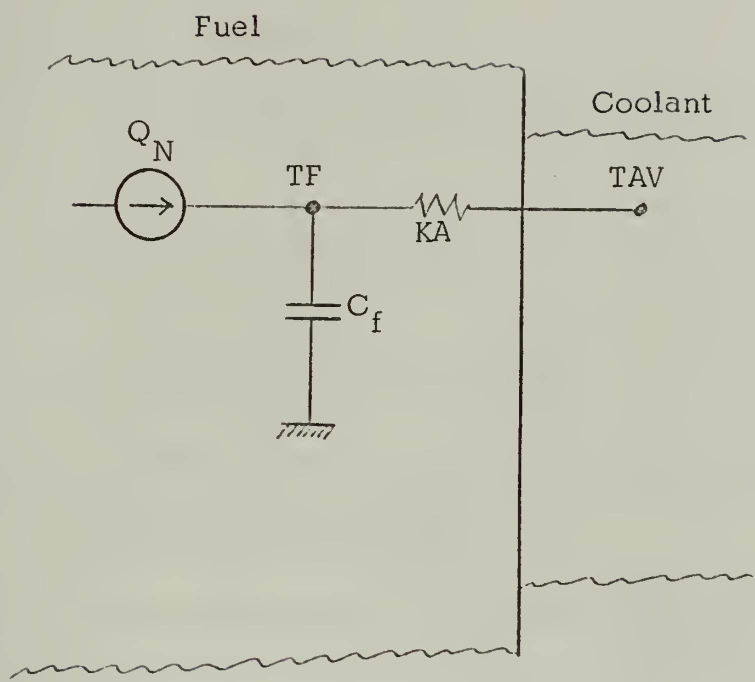


Fig. 8. Heat flow model.

The definition of the heat capacitance is [7]

$$C = \frac{\Delta\ Q}{\Delta\ T} \qquad \frac{cal}{sec}$$

Therefore the above equation may be written as

$$\frac{dTF}{dt} = \frac{1}{\tau}\ (TAV - TF) + A'\ N \tag{III.17}$$

where $\dfrac{1}{\tau} = \dfrac{K\ A}{c_f} \quad \left[\dfrac{cal}{sec\ cm^2\ °C} \cdot cm^2 \cdot \dfrac{°C}{cal} \quad \dfrac{1}{sec}\right]$

$\quad = $ fuel time constant

$$A' = \frac{A}{c_f}$$

= Proportionality factor

b. Heat Removal

The amount of heat removed by the coolant is given as

$$Q = \beta \cdot A_c \cdot V \cdot C \cdot \Delta T \qquad \text{(III.18)}$$

where β = density of coolant $\left[\frac{gm}{cm^3}\right]$

A_c = cross sectional area of coolant passage $[cm^2]$

V = coolant speed $\left[\frac{cm}{sec}\right]$

C = specific heat of coolant $\left[\frac{cal}{gm\ °C}\right]$

ΔT = coolant temperature rise within the element [°C]

As shown earlier the temperature rise of the coolant is not a linear function of the position of a unit element within the coolant channel. A second nonlinearity accours in the coolant channel which is shown in Fig. 9. The temperature of

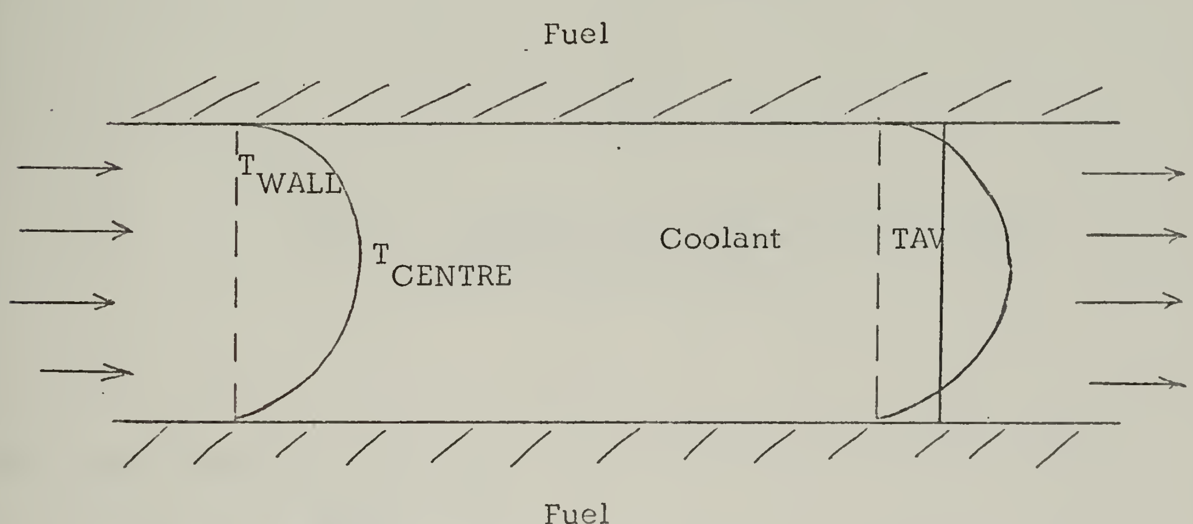


Fig. 9. Temperature in coolant path.

coolant at the walls of the fuel element are higher than at the center of the coolant channel. This nonlinearity may be neglected for the reasons stated earlier, and an average temperature profile will be assumed as shown in Fig. 9. The specific heat of the coolant and the coolant density will be assumed constant. The heat balance equation for the dynamic case is again derived with the aid of an electrical equivalent as shown in Fig. 10.

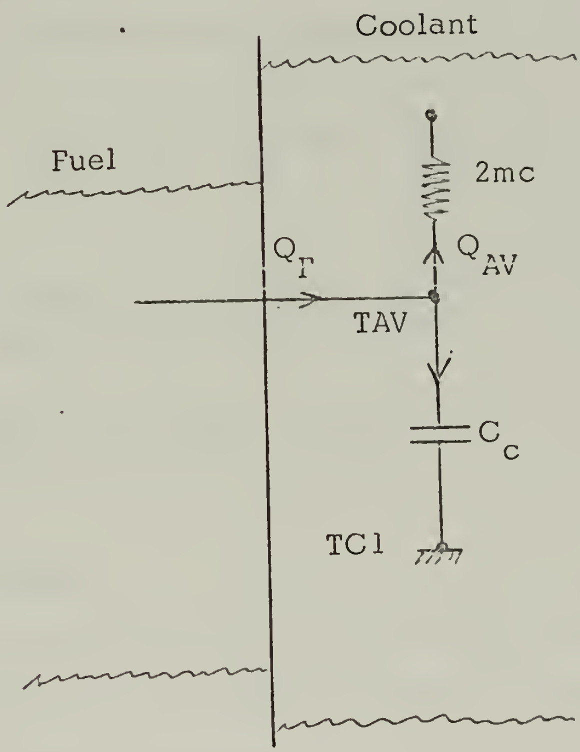


Fig. 10. Electrical equivalent for heat removal by coolant from core.

The heat flow equation is

$$Q_F = C_c \frac{dTAV}{dt} + Q_{AV} \qquad \text{(III.19)}$$

where $Q_{AV} = Q$ (from equation III.18)

which may also be written as

$$Q_{AV} = m\ c\ \Delta T$$
$$= m\ c\ (TC1 - TH1)$$

where m = coolant flow rate $\left[\frac{gm}{sec}\right]$

After rearranging and using the relation

$$TAV = \frac{TC1 + TH1}{2}$$

to eliminate TH1, the following equation is obtained

$$\frac{dTAV}{dt} = - \frac{1}{\tau_2} + \frac{1}{\tau_2'} \quad TAV + \frac{1}{\tau_2} TF + \frac{1}{\tau_2'} TC1 \qquad \text{(III.20)}$$

where $\frac{1}{\tau_2} = \frac{KA}{C_c} \quad \left[\frac{cal}{sec\ cm^2\ °C}\ cm^2\ \frac{°C}{cal} \rightarrow \frac{1}{sec}\right]$

$$\frac{1}{\tau_2'} = \left[\frac{2mc}{C_c} \quad \frac{gm}{sec}\ \frac{°C}{cal}\ \frac{cal}{gm\ °C} \rightarrow \frac{1}{sec}\right]$$

2. <u>Heat Exchanger</u>

Assuming no heat loss to the outisde the following relation holds: The total change in heat of the secondary sodium within the heat exchanger.

$$\Delta Q_1 = \Delta Q_2 \qquad \text{(III.21)}$$

where $\Delta Q_1 = m\ c(TBI1 - TBO1)$

= the heat transferred from the primary sodium

$\Delta Q_2 = KA\ (TB1 - TB2)$

= the heat transferred to the secondary sodium

Using average temperature of primary and secondary side.

Equation III.21 becomes now

$$KA(TB1 - TB2) = m\,c(TBI1 - TBO1) \qquad (III.22)$$

or, after using the relation

$$TBI = \frac{TBI1+TBO1}{2}$$

$$TBI1-TB2 = \frac{1}{M1}\,(TBI1-TB1)$$

where $M1 = \frac{2\,m\,c}{KA}$ $\left[\frac{gm}{sec}\;\frac{cal}{gm\ °C}\;\frac{sec\ cm^2\ °C}{cal}\;\frac{1}{cm^2} \rightarrow \text{dimensionless}\right]$

If now, as done before, the heat flow rate, heat capacitance of the primary sodium and the overall transfer coefficient is assumed constant, M1 may be seen as a heat exchanger constant.

The dynamic equation for the secondary side is derived as in section II.B.1.b.

$$Q_P = C_S \frac{dTB2}{dt} + Q_S$$

where $Q_P = KA\ (TB1 - TB2)$

$Q_S = m\ c\ (TH2 - TC2)$

C_S = heat capacitance of secondary sodium

or after rearranging

$$\frac{dTB2}{dt} = -\left(\frac{1}{\tau_3} + \frac{1}{\tau_3'}\right) TB2 + \frac{1}{\tau_3}\,TB1 + \frac{1}{\tau_3'}\,TC2 \qquad (III.23)$$

where $\frac{1}{\tau_3} = \frac{KA}{C_S} \quad \left[\frac{1}{sec}\right]$

$$\frac{1}{\tau_3'} = \frac{2\ m\ c}{C_S} \quad \left[\frac{1}{sec}\right]$$

3. Steam Generator

Since the flow of secondary sodium through the steam generator can be changed by the bypass valve in the secondary circuit the flow rate of sodium through the steam generator will be defined as $x \cdot m$, where x is the valve opening $(0 < x < 1)$.

$x = 1$ valve fully open (100% flow rate)

$x = 0$ valve completely closed

As in section II.B.2. the following equation is obtained

$$KA(TB3 - TS) = x\ m\ c(TBI2 - TBO2) \qquad \text{(III.24)}$$

eliminating TBO2 and rearranging gives

$$TB3 - TS = \frac{x}{M2}\ (TBI2 - TB3)$$

where $M2 = \frac{2\ m\ c}{KA}$

= a dimensionless steam generator constant under the assumptions of section II.B.2.

For the dynamic equation of the steamside, the principle used in section II.B.1.b. is again applied and the following equation obtained

$$\dot{Q}_P = C_S \frac{dT_S}{dt} + \dot{Q}_S \qquad \text{(III.25)}$$

where $Q_P = KA\,(TB3 - TS)$

C_S = heat capacitance of the steam

Q_S = heat consumed by the steam plant

From the Carnot cycle it is known, that the work done in a thermodynamic machine is proportional to the difference of the added and rejected heat.

$$W \propto (Q_A - Q_R)$$

but $Q_S = Q_A - Q_R$

and Q_A is proportional to the entrance temperature to the steam plant and Q_R is proportional to the steam outlet temperature. Taking the average temperature it is seen that

$$Q_S \propto TS \propto W$$

from this relation Q_S may be written as

$$Q_S = K \cdot \psi \cdot TS$$

K = constant, assuming, constant flowrate, heat capacitance and linear temperature change with respect to pressure over the range of operation $\left[\frac{\text{cal}}{°\text{C}}\right]$.

ψ = dimensionless proportionality factor for the load demand $(0 < \psi < 1)$

$\psi = 1 \rightarrow 100\%$ load

$\psi = 0 \rightarrow 0$ load

equation (III.25) is then

$$KA(TB3 - TS) = C_S \frac{dTS}{dt} + K \cdot \psi \cdot TS$$

and after rearranging

$$\frac{dTS}{dt} = -\left(\frac{1}{\tau_5} + K'\psi\right) TS + \frac{1}{\tau_5} TB3 \qquad \text{(III.26)}$$

where $K' = \frac{K}{C_S} \left[\frac{cal}{°C}\,\frac{°C}{cal} \rightarrow \text{dimensionless}\right]$

$$\frac{1}{\tau_5} = \frac{KA}{C_S} \left[\frac{1}{sec}\right]$$

C. HEAT TRANSPORT

To obtain dynamic equations which include the time delays present within the heat transport system of the plant, the Taylor series expansion will be used. Throughout this section it will be assumed, that there is no heat loss during the heat transport from one plant component to another.

1. Primary Circuit

The transport delay, i.e., the time it takes for one unit volume element of sodium to get from the exit of the reactor (with temperature TH1) to the entrance of the heat exchanger (still with temperature TH1, but now called TBI1) is designated T4. Thus

$$TH1 = TBI1$$

but $TH1(t) = TBI1\ (t + T_4)$ (III.27)

Expanding the right side of equation (III.27) in a Taylor series

$$TBI1(t+T_4) = TBI1(t) + T_4 \frac{dTBI1(t)}{dt} + H.O.T. \qquad \text{(III.28)}$$

where H.O.T. = higher order terms.

Assuming slow temperature changes, which is reasonable for a large stationary power plant, all higher order terms may be neglected.

Replacing TH1 and rearranging, equation (III.27) may be written as

$$\frac{dTBI1}{dt} = - \frac{1}{T_4} TBI1 + \frac{2}{T_4} TAV - \frac{1}{T_4} TC1 \qquad \text{(III.29)}$$

For the transport delay from the heat exchanger back to the reactor the same time duration will be assumed.

Therefore TBO1 = TC1

$$\text{but } TBO1(t) = TC1\ (t + T_4) \qquad \text{(III.30)}$$

Using again Taylor series expansion, replacing TBO1 and rearranging, the dynamic equation for the heat transport from the heat exchanger back to the reactor is given as

$$\frac{dTC1}{dt} = - \frac{1}{T_4} TC1 + \frac{2}{T_4} TB1 - \frac{1}{T_4} TBI1 \qquad \text{(III.31)}$$

2. Secondary Loop

The heat flow diagram for the secondary sodium loop is shown in Figure 11 where Q_n ($n = 1,2,\ldots,5$) is the rate at

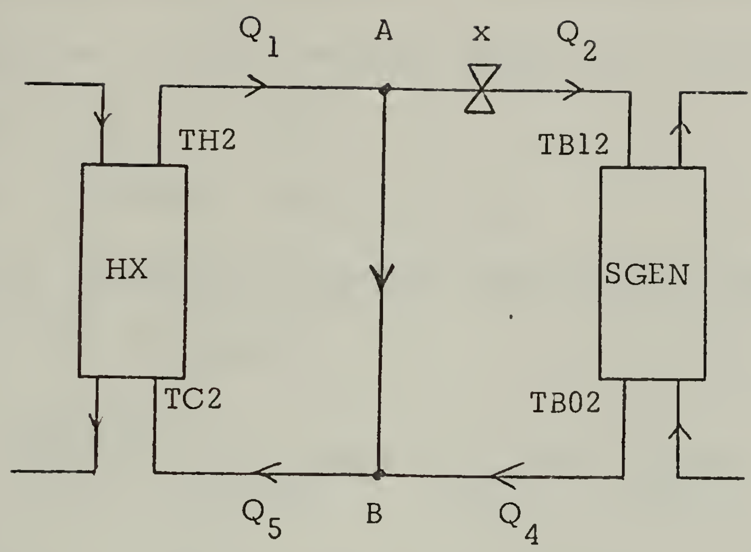


Fig. 11. Heat flow diagram for secondary circuit.

which heat is transported by a unit volume element. The function of the bypass valve X is to increase or decrease the amount of sodium flow through the steam generator: it does not influence the temperatures. This may be shown as follows: using the equivalent of an electric circuit, the "model equation" for node A is written:

$$Q_2 = Q_1 - Q_3 \qquad \text{(III.32)}$$

$$x\ m\ \ c\ \ TBI2 = m\ \ c\ \ TH2 - (1 - x)m\ \ c\ \ TH2$$

$$x\ TBI2 = TH2 - (1-x)\ TH2$$

$$TBI2 = TH2$$

Therefore the same procedure as in section III.C.1, may be used to arrive at a dynamic equation for the heat transport delay from the heat exchanger to the steam generator. The time duration of the transport delay will be called T_5.

Since $TH2 = TBI2$

and $TH2(t) = TBI2\ (t + T_5)$

and, again using Taylor series expansion for $TBI2(t + T_5)$ and replacing TH2 (t) gives

$$\frac{dTBI2(t)}{dt} = -\frac{1}{T_5} TBI2 + \frac{2}{T_5} TB2 - \frac{1}{T_5} TC2 \qquad \text{(III.33)}$$

For the heat transport from steam generator to heat exchange the "nodel equation" for "node" B is

$$Q_5 = Q_3 + Q_4 \qquad \text{(III.34)}$$

$$\dot{m}\, c\ TC2 = x\, \dot{m}\ c\ TBO2 + (1-x)\ \dot{m}\ c\ TH2$$

Assuming that the duration of the transport delay is again T_5 for the flow through the bypass and for the flow from the steam generator, equation (III.34) becomes

$$TC2(t + T_5) = x\ TBO2(t) + (1-x)\ TH2(t) \qquad \text{(III.35)}$$

Replacing TBO2 and TH2, using the relations

$$\frac{M_2}{x} = \frac{TBI2 - TB3}{TB3 - TS}$$

$$TB3 = \frac{TBI2 + TBO2}{2}$$

$$TB2 = \frac{TC2 + TH2}{2}$$

and expanding TC2$(t + T_5)$ in a Taylor series, equation (III.35) becomes

$$\frac{dTC2}{dt} = -\frac{1}{T_5{}'} TC2 + \frac{1}{T_5{}''} TB2 + \frac{1}{T_5{}'''} TS + \frac{1}{T_5{}^{IV}} TBI2 \qquad \text{(III.36)}$$

where

$$T_5{}' = \frac{T_5}{2-x}$$

$$T_5{}'' = \frac{T_5}{2-2x}$$

$$T_5{}''' = \frac{T_5(x+M2)}{2x\ M2}$$

$$T_5{}^{IV} = \frac{T_5(x+M2)}{x(x-M2)}$$

IV. SYSTEM SIMULATION

A. ANALOG COMPUTER PROGRAMMING

The coefficients of the differential equations developed in section II were calculated for a steady state solution (see Appendix C). Using the numerical values of these coefficients the following set of equations which describe the dynamic behaviour of the plant was obtained:

$$\dot{D} = .58(N-D)$$

$$\dot{TF} = -.5\ TF + .5\ TAV + 725\ N$$

$$\dot{TAV} = -.5333\ TAV + .5\ TF + 4.8333\ TC1$$

$$\dot{TC1} = -.25\ TC1 - .0988\ TBI1 + .3488\ TB2$$

$$\dot{TBI1} = -.25\ TBI1 + .5\ TAV - .25\ TC1$$

$$\dot{TB2} = -6.9626\ TB2 + 3.0233\ TBI1 + 3.9394\ TC2$$

$$\dot{TBI2} = -.25\ TBI2 + .5\ TB2 - .25\ TC2$$

$$\dot{TC2} = -.2625\ TC2 + .275\ TS - .0375\ TB2 + .025\ TB2$$

$$\dot{TS} = -.0421\ TS - .0168 \cdot \psi \cdot TS + .0421\ TBI2$$

$$N = D / (1-K_T)$$

To simulate these equations on an analog computer and to obtain maximum accuracy, the gain coefficients must to be scaled with respect to the maximum voltage level of the analog computer (see Appendix D). The scaled equation used for the simulation are given below.

$$\dot{D} = .58\ (N-D)$$

$$\dot{TF} = -.5\ TF + .1833\ TAV + .4833\ N$$

$$\dot{TAV} = -5.3333\ TAV + 1.3636\ TV + 4.3939\ TC1$$

$$\dot{TC1} = -\ .25\ TC1 - .1235\ TBI1 + .3314\ TB2$$

$$\dot{TBI1} = -\ .25\ TBI1 + .44\ TAV - .2\ TC1$$

$$\dot{TC2} = -\ .2625\ TC2 + .2895\ TS - .0474\ TBI2 + .025\ TB2$$

$$\dot{TB2} = -6.9626\ TB2 + 3. + 78\ TBI1 + 3.9394\ TC2$$

$$\dot{TBI2} = -\ .25\ TBI2 + .3958\ TB2 - .1979\ TC2$$

$$\dot{TS} = -\ .0421\ TS - .0168 \cdot 4 \cdot TS + .0505\ TBI2$$

$$N = D/(1-K_T)$$

The temperature variables for example are no longer in °F but in volts.

A block diagram, using both the symbols shown below and a linear flowgraph for representing the analog computer setup may now be drawn (Figure 13, 14). (See Appendix E for the analog computer diagram corresponding to the flowgraphs shown in Figure 14)

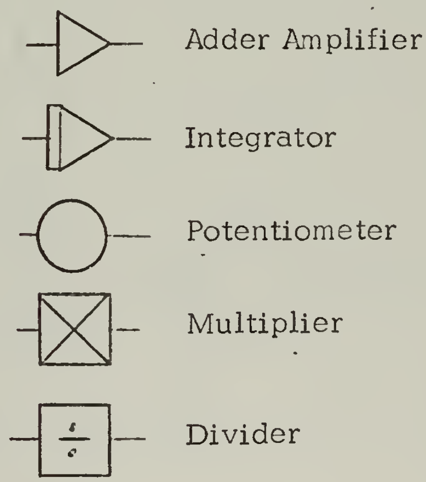


Figure 12. Symbols for analog computer components

It proved very valuable to write a simple Fortran executive program which performed the above calculations each time a

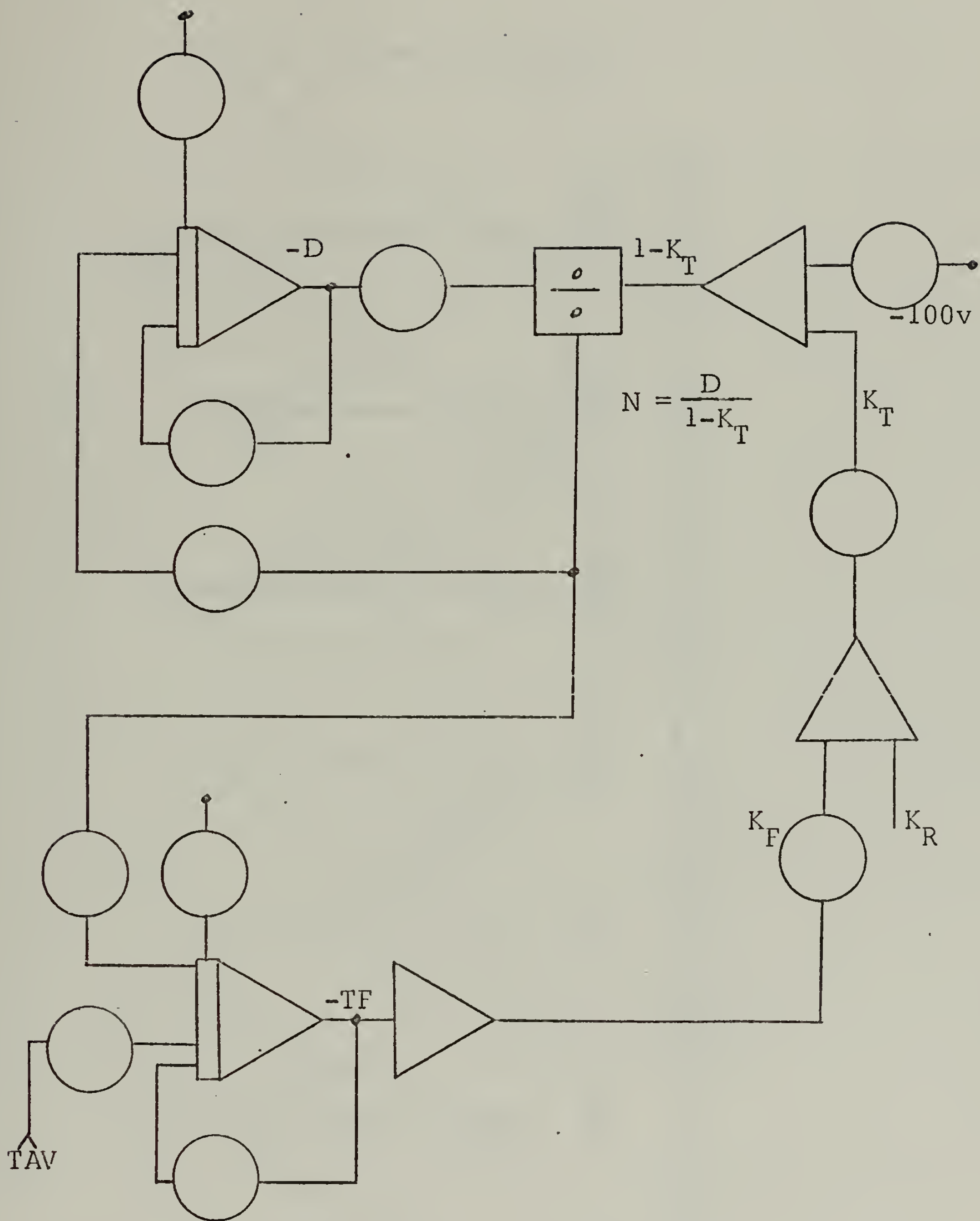


Fig. 13. Analog Computer setup - reactor core.

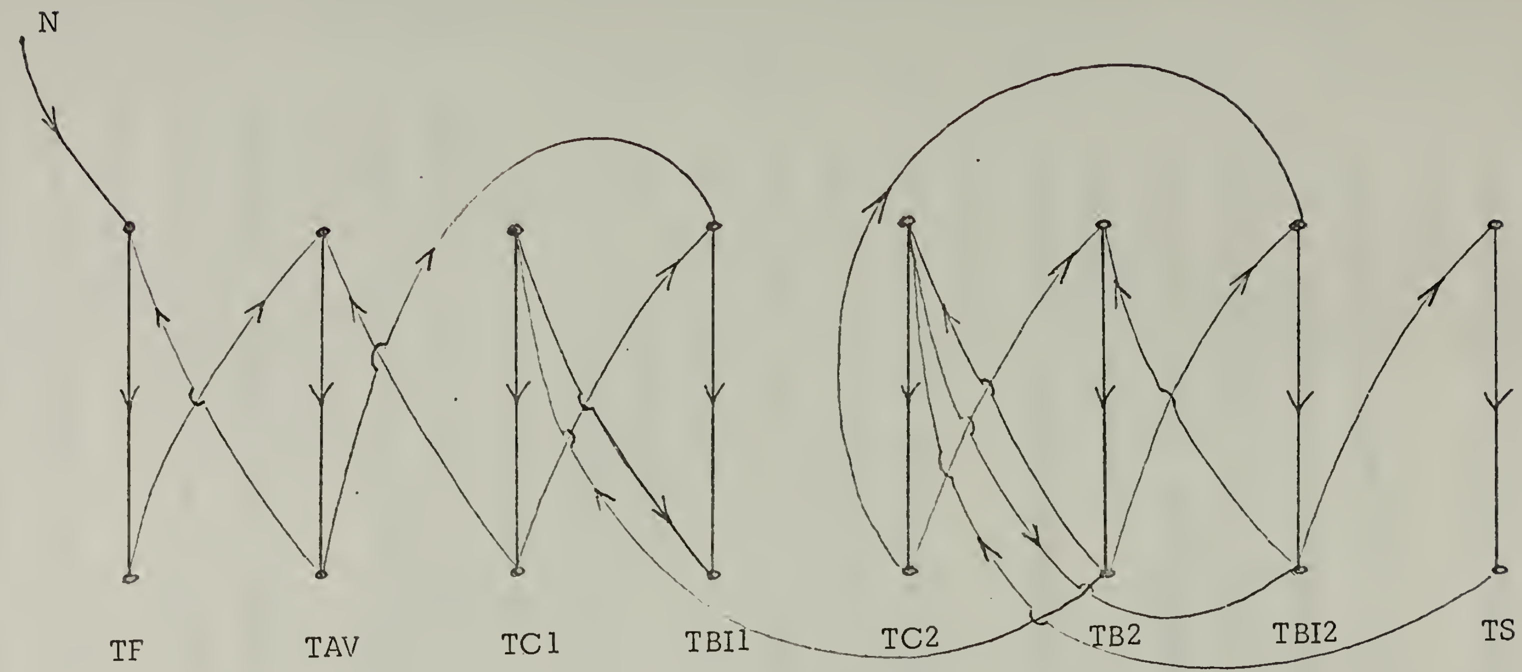


Fig. 14. Linear flowgraph for heat transfer, heat transport, heat removal (path gains omitted).

test or simulation run was made. This program contained the following steps:

a) Read in steady state plant variable values, constants and chosen maximum plant variable values

b) Calculate the numerical value for the coefficients of the differential equations

c) Calculate magnitude scaling factors

d) Calculate scaled coefficients for the analog computer components

e) Calculate initial conditions for analog integrators

f) Write out all calculated values and the scaled and unscaled differential equations

g) Calculate the initial steady-state output values of the amplifiers

h) Set all potentiometers

i) Scan all amplifiers and compare with calculated values, write out errors

The amount of time saved by using this executive program during the many runs performed was appreciable. The program had the following advantages:

a) Equipment failures were detected immediately and isolated to only a few components by the test part of the program.

b) The scaling procedure was done by the computer. Since the maximum plant variable values were not known, the optimum scaling coefficients had to be found by trial

and error in many runs.[1] By just changing one statement in the program (maximum variable value) the analog computer was ready for the next run within seconds.

c) The documentation was done automatically by the digital computer.

B. DYNAMIC CHECK

A theoretical curve describing the behaviour of the reactor of the proposed plant following an accidental reactivity input was available from Ref. [2]. The validity of the dynamic equations describing the reactor was demonstrated with the aid of this curve.

To check the solution of the analog computer the system equations were also solved on a digital computer (IBM 360/67) using a fourth order Runge Kutta routine with accuracy testing of single and double increment and double precision calculation. The results of these dynamic checks are stated below.

1. Controlled Accidental Reactivity Input

The accident considered assumes that two control rods drop into the core. This would correspond to a reactivity insertion of 100 $/sec. It is further assumed that scram Action takes place .2 sec. after the accident starts.

A solution of the system equation to this accident was obtained on the digital computer with the above described routine.

---

[1]Because of the nonlinearities in the plant dynamic equations, an analytical solution for the calculation of the maximum values cannot readily be obtained.

The digital computer solution gave exactly the same results for the temperature variables TAV and TF. The numerical values for the neutron density N(t) varied slightly in magnitude and in the time of occurance. This slight difference can be explained by the simplifying assumptions which were made in deriving equation II.5 and II.6. The one group delayed neutron and the prompt jump approximation effects the time of occurance of the maximum value of N(t). By neglecting small reactivity coefficient (equation II.10) the magnitude of N(t) is influenced. In spite of this small difference in the result, the equations used for the simulation of the reactor core are thought to be accurate, especially since, as stated above, the temperature TAV and TF followed very precisely the given data.

2. Change in Load

The first part of the check on the accuracy of the analog computer solution was made by obtaining a digital computer solution to a load change in the form of a step change of magnitude - 20% for 20 sec. The results are given in Table I and in Figure 15.

3. Change in Reactivity

A second digital computer check of the analog computer solution consisted in introducing a disturbance in the reactivity input in the form of a +20 percent reactivity step change for 20 sec. The results are given in Table II and in Figure 16.

Time(sec)	TCI(°F)	TB2(°F)	TS(°F)
0	800.2	885.1	750.2
2	801.1	886.6	762.3
4	803.9	890.4	773.1
6	808.2	895.5	782.9
8	813.3	901.5	791.9
10	820.2	908.6	800.2
15	835.3	924.9	818.5
20	840.1	941.5	834.7
22	844.6	946.5	827.6
24	852.2	948.5	821.7
26	857.4	948.8	816.9
28	858.3	948.1	812.9
30	860.6	946.8	809.2
35	855.2	942.2	804.0
40	850.4	937.3	800.0

TABLE I

Digital computer results; temperature changes due to step change in load of -20% for $0 < t < 20$ sec.

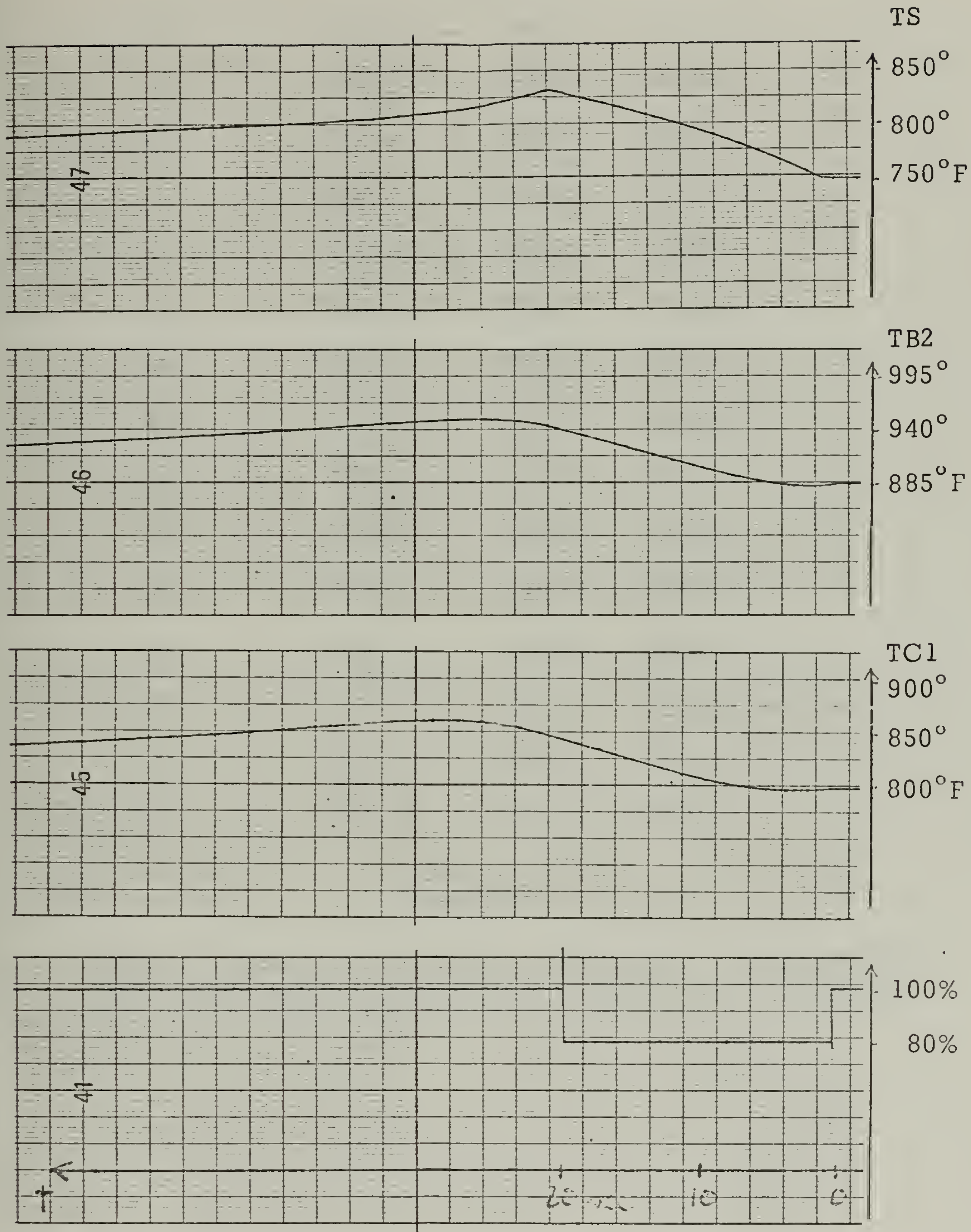


Fig. 15. Analog computer results Load change as in table I.

Time(sec)	TCI(°F)	TB2(°F)	TS(°F)
0	800.1	885.1	750.2
2	800.3	887.8	750.2
4	801.1	891.6	750.5
6	802.2	893.9	751.0
8	803.3	895.5	751.8
10	804.3	896.8	752.8
15	806.5	899.4	755.8
20	808.9	901.8	758.9
22	809.7	900.6	760.2
24	810.0	897.9	761.0
26	810.0	896.4	761.7
28	810.0	895.6	762.0
30	810.0	895.3	762.0
35	810.4	895.2	761.4
40	810.6	895.0	760.5

TABLE II

Digital computer results; temperature changes due to step change in reactivity input of + 20 cents for 0 < t < 20 sec.

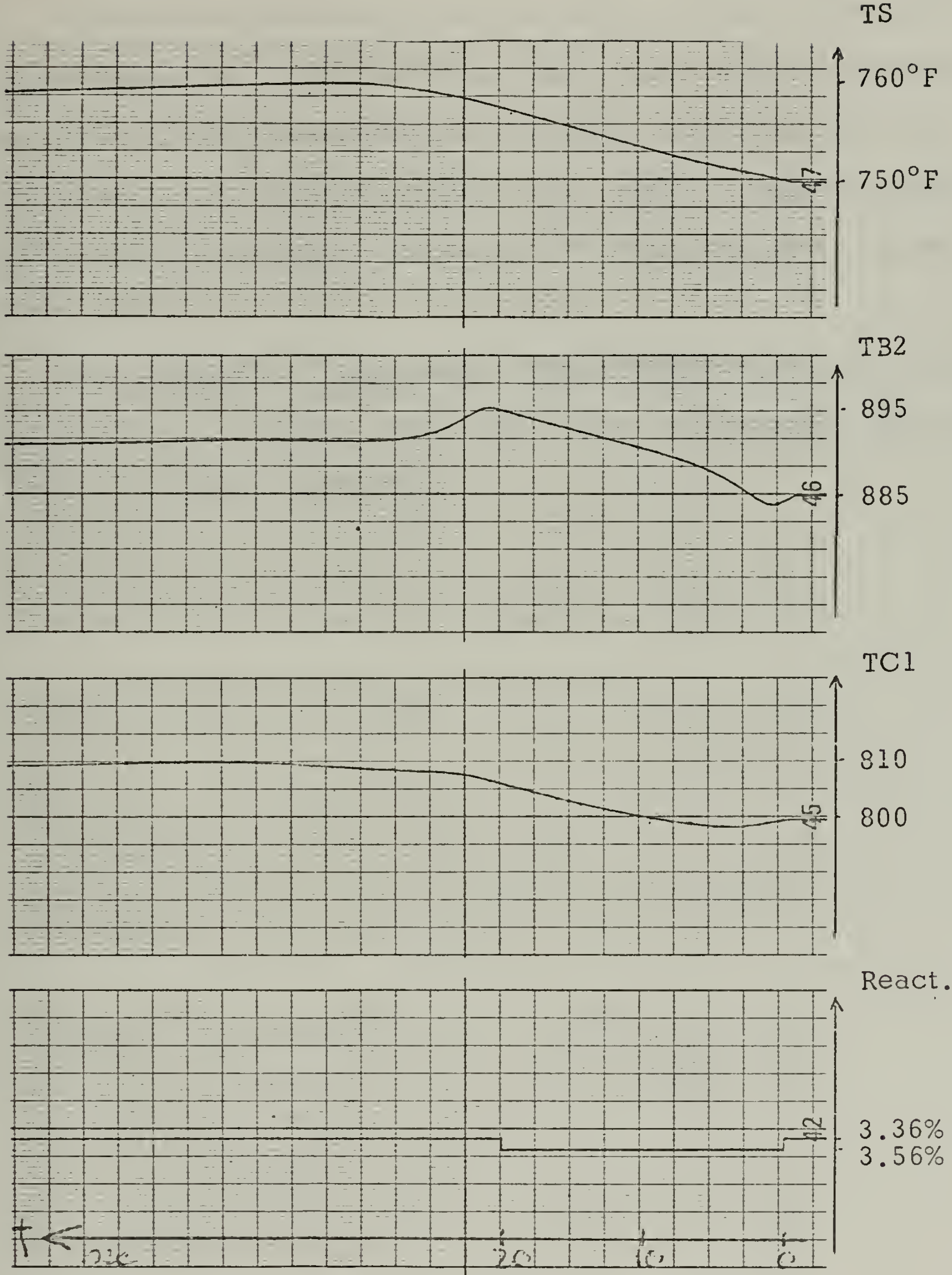


Fig. 16. Analog computer results Reactivity change as in table II.

4. Discussion of the Dynamic Check Results

It can be observed from the above results that the developed equations are valid for the plant under consideration. Comparison of the given digital computer solution and the analog computer graphs shows that the analog computer gives a solution which is within the bound of less then one percent exact ($\pm$ .5%).

The results of the tests have demonstrated the validity of the simulation within the above bound of accuracy and under the earlier made assumptions.

VI. CONTROLLER

A. CONTROL STRATEGY

The inherent incapability of the plant to follow load changes which is due to the small reactivity feedback coefficient of the coolant, is a disadvantage in the control of a Fast Breeder Reactor. It makes complete control of the coolant temperature in the reactor necessary. An automatic controller for power level control must be developed whose two main purposes are

a) coolant temperature level must be kept constant to obtain optimum breeding ratio and optimum performance of the reactor and

b) steam conditions are to be kept constant for optimum performance of the steam plant.

On the other hand several advantages which are inherent for the plant help the controlling action to achieve smooth and efficient power level changes. The reactor is automatically isolated from the load by the secondary sodium loop and to a certain degree by the primary sodium loop. Therefore, the inlet temperature to the core changes only very slowly. These two circuits also serve as a heat reservoir. This allows a temporarily larger rate of load change than the rate of power change which the reactor can achieve.

The rate of power change obtained from the reactor is limited by the maximum rate of change of reactivity. This

value is taken as 2^{cents}/sec. [2] It is also limited by mechanical factors such as thermal stress within the reactor, heat exchanger or steam generator and speed of mechanically driven valves. The thermal stresses were not investigated here, it can, however, be stated that in none of the test runs the limiting values for the rate of change of temperature, e.g. the coolant in the core with 100°F/sec., as given in Ref. [2], was observed. The limiting factor in this investigation was found to be the rate of change of reactivity.

The control strategy is based on the following thoughts:

Because of the extreme long time constant, a pure proportional controller, which acts only following the occurance of errors in the to-be-controlled quantities was not sufficient. Therefore, an anticipatory or derivative control had to be implemented. To get the best derivative control action signal, the derivative or the rate of change of temperatures which had to lead to changes in the to-be-controlled temperature had to be sensed at the earliest possible time. This steady state - or at most very slow power level change - strategy is not valid for larger power level changes. In this case preprogrammed controlling action had to be implemented.

B. CONTROLLER DESIGN

The choice was given between a pure analog-logic controller or a digital controlling program.

The analog controller had the advantage that it could have been implemented comparitively easy for a plant simulation of this size. On the other hand it was felt to be more realistic

to design an automatic controller which uses the digital computer since modern power plants are equipped with digital computers used for many purposes - from bookkeeping of the plant datas to paycheck writing - that a digital controller would represent only a small and comparitively low cost addition to the main computer. Investigations have also shown [8], that for large scale plant controllers digital controllers become more economical than analog controllers. Therefore, it was decided to design a digital controller. The following controlling devices were "built" in to the plant:

a) control rods. It was assumed that the rate of change of reactivity could be varied. For the preprogrammed controlling action the maximum rate of 2 cents/sec. was assumed; for the steady state controlling action a value of .1 times the maximum rate was found by experiment to give the smoothest control dynamics.

b) Bypass valve in secondary circuit. The opening time (with maximum speed) for the preprogrammed phase was assumed to be 20 sec. from completely closed to fully open; for the small controlling action .2 of this value was used.

Because of the constantly changing value of the bypass valve opening, several gain factors in the dynamic equations developed in section II changed during operation. As a result of this the analog computer setup had to be modified (see Appendix E).

The above described controlling devices where controlled by the digital computer which in turn received the data from the simulated plant on the

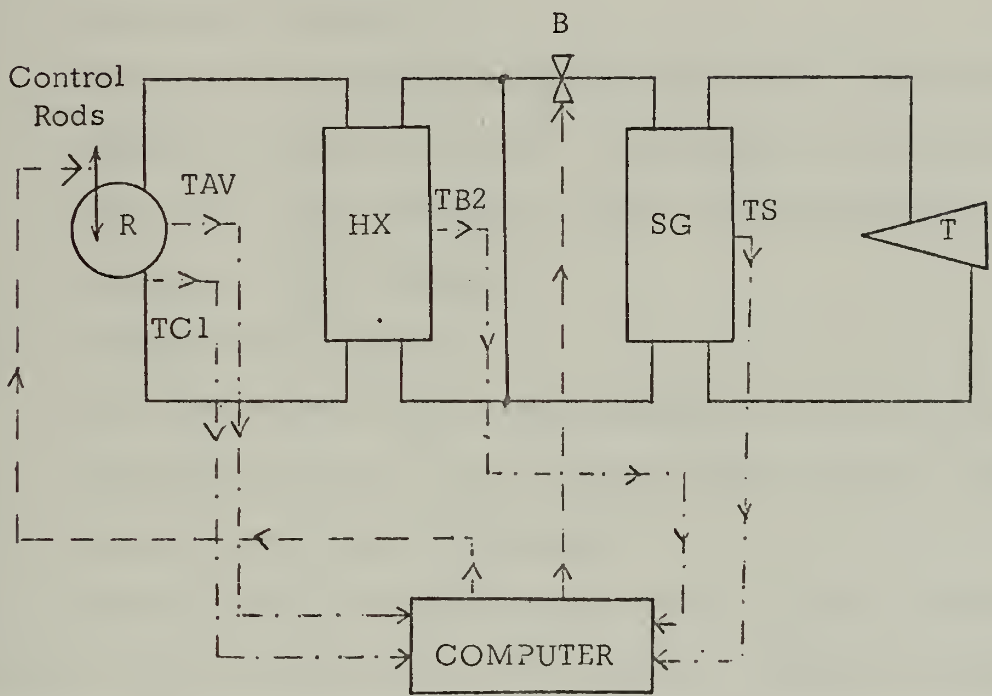


Fig. 17. Plant and control points.

analog computer (see Fig. 17).

The control strategy called for

a) preprogrammed power level change control. The control trajectory for this control was obtained by introducing load changes and correcting the errors in TC1 and TS with manually operated potentiometer, which simulated

control rods and bypass valve opening. The resulting datas were evaluated with the aid of a least square straight line approximation program to give the control trajectory for the control reactivity and valve opening as a function of the load (see Appendix F).

b) Derivative control.

Following the thought described in IV.1, the rate of change in TAV and TB2 were calculated by storing values every 10^{th} of a second and then calculating the rate of change over one second.

c) Proportional control.

The to-be-controlled temperatures TC1 and TS were compared every 10^{th} of a second with the set value and the error was calculated.

To take the addition of noise in actual plant measured variables into consideration, all measured values were put into a dead zone. This had also the advantage of smoothing the controlling action.

A flow chart of the basic program for the digital controller is given in Figure 18. The individual parts of the program are described in detail in Appendix G.

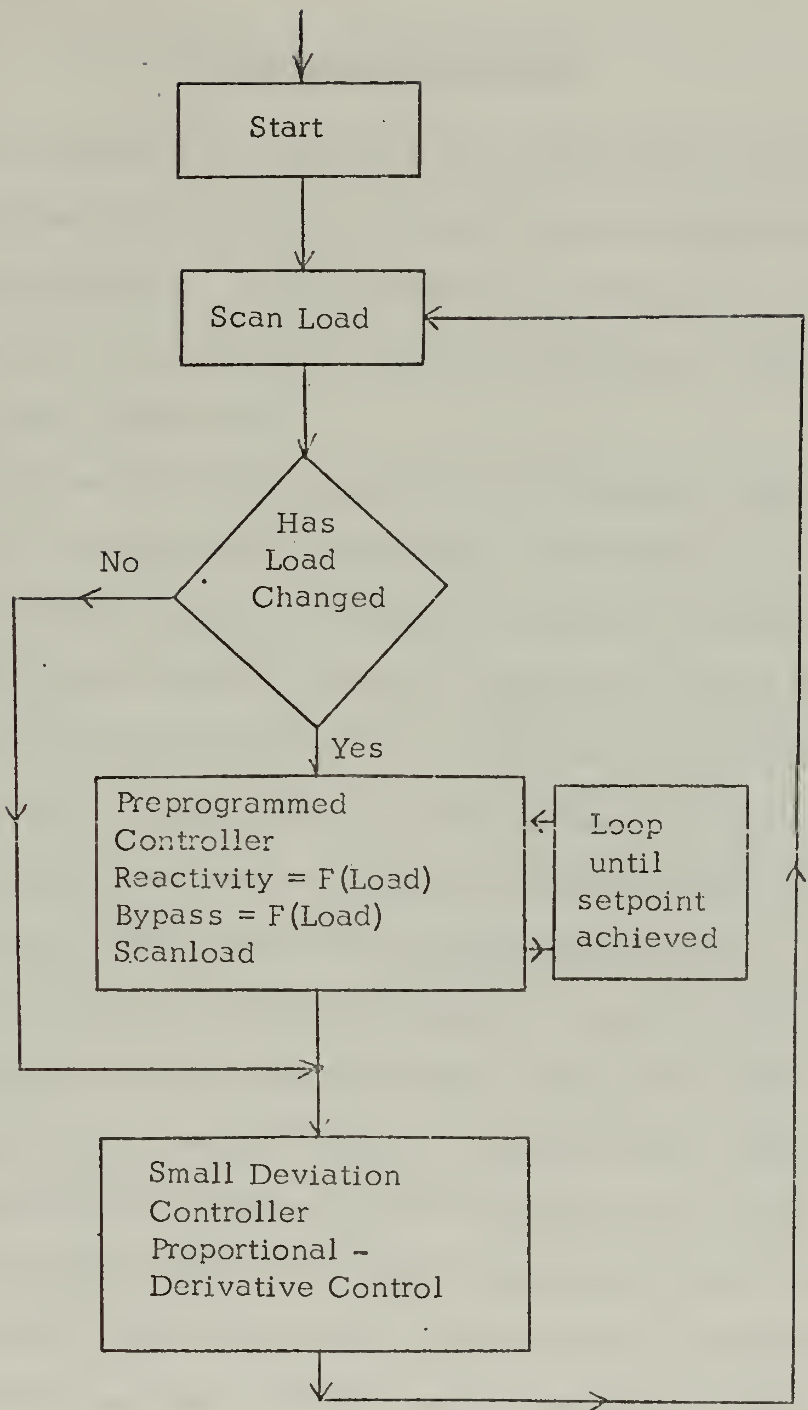


Fig. 18. Flow chart for digital controller.

VI. RESULTS AND COMMENTS

The results which were achieved by controlling the plant with the described controller are shown in this section as stripchart recordings in Figure 19 through Figure 21. The test inputs were step changes in load of different sizes and at different time intervals.

Figure 19 shows the plant dynamics following a step change in load of -50%. This step change does not seem to be very realistic, it proves, however, that the initial overshoot in the to-be-controlled temperatures of little more than 100°F is damped down very effectively to a secondary overshoot - or first undershoot - of about 20°F. The initial overshoot cannot be avoided since the controlling devices work at maximum allowable speed during the preprogrammed part. The same statements hold for the step change in load of +50% which was introduced after the transients had almost settled. Even a load change of this amount does not endanger the plant - due to the fast working and direct preprogrammed controller - which may be seen from the value of N which increases only about 12%.

It is believed, that this test input and the resulting transient demonstrate the validity and necessity of the division of the control program into its two main parts, it also demonstrates effectiveness of the preprogrammed controller.

Figure 20 shows the plant dynamics following a step change of different magnitudes and at time intervals which

are shorter than the settling time of the dynamics. A 20% step change in load produces only a 25°F, or 35°F respectively, overshoot in the controlled temperature. The increase in N is only 4%. The interplay of preprogrammed and small deviation control may also be seen from Figure 20 by considering the reactivity and bypass valve curve.

Figure 21 was taken over a time of more than 1 hour. Though step changes in load of 10% do not seem to be very practical this recording shows a more realistic picture of the plant controller. It especially proves the accuracy of the steady state controller. After the settling of the dynamics this controller is able to keep the error in the controlled temperatures within a bound of less than $\pm$ 3°F at a controlled temperature level of 800°F for TCI and 750°F for TS.

The above results demonstrate the effectiveness of the designed controller for the plant layout simulated in this investigation. Since conventional stability calculations like root-locus plot, Bode plot or Nyquist diagram cannot be applied directly to a controller of the kind developed here, this topic is not included in this report. It can however be stated that no instabilities following any of the applied load changes were observed during the simulation.

The addition of more plant components in the simulation of the system will, as stated in section II, not change the basic form of the dynamic system equation. It will however, change the dynamic response to a certain degree. The same is true for the nonlinearities which were not taken into account in the simulation in this report.

Further investigations can include the above considerations, however, a simulation of a complete plant which includes all components and takes all nonlinearities into account is only possible on a very large scale digital, or better, hybrid computer. If a computer of this size is not available an accurate simulation can be done component by component as in Ref. [3] for a LMFBR. Accurate stability investigation may then be performed by simulation.

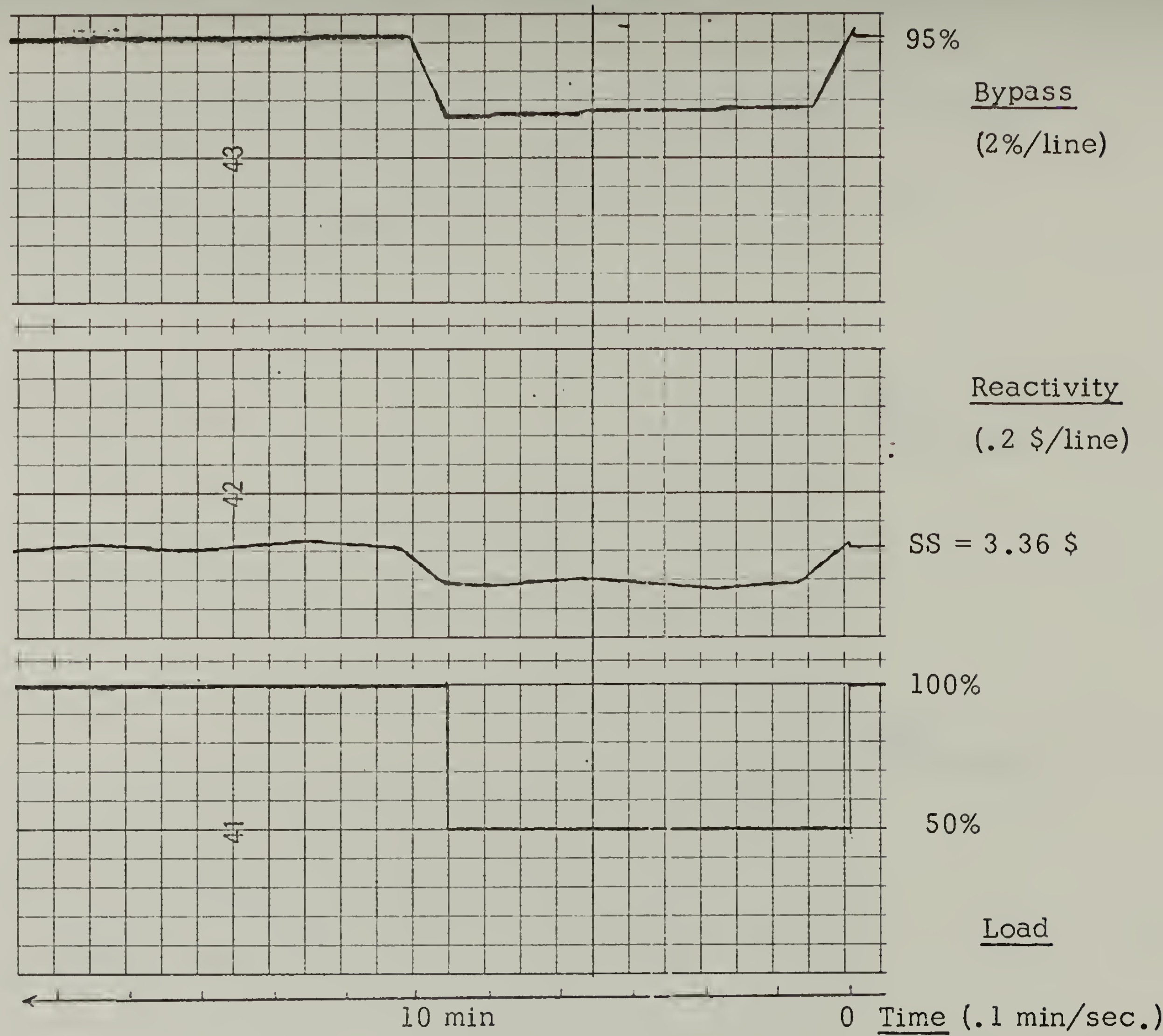


Fig. 19. Loadchange (50% Step) with control action.

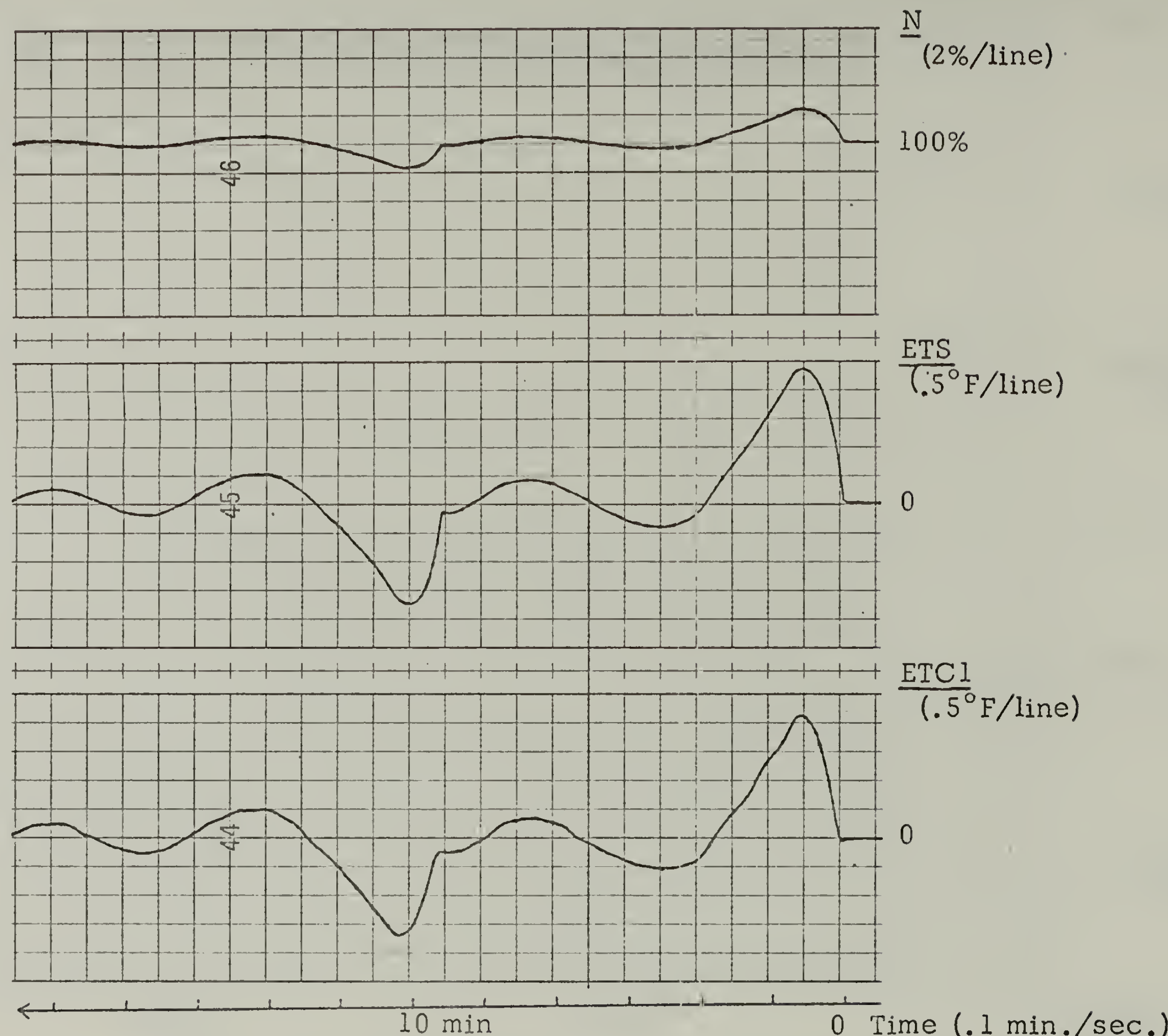

N
(2%/line)
100%
46
ETS
(.5°F/line)
0
45
ETC1
(.5°F/line)
0
44
10 min
0 Time (.1 min./sec.)

Fig. 19a.

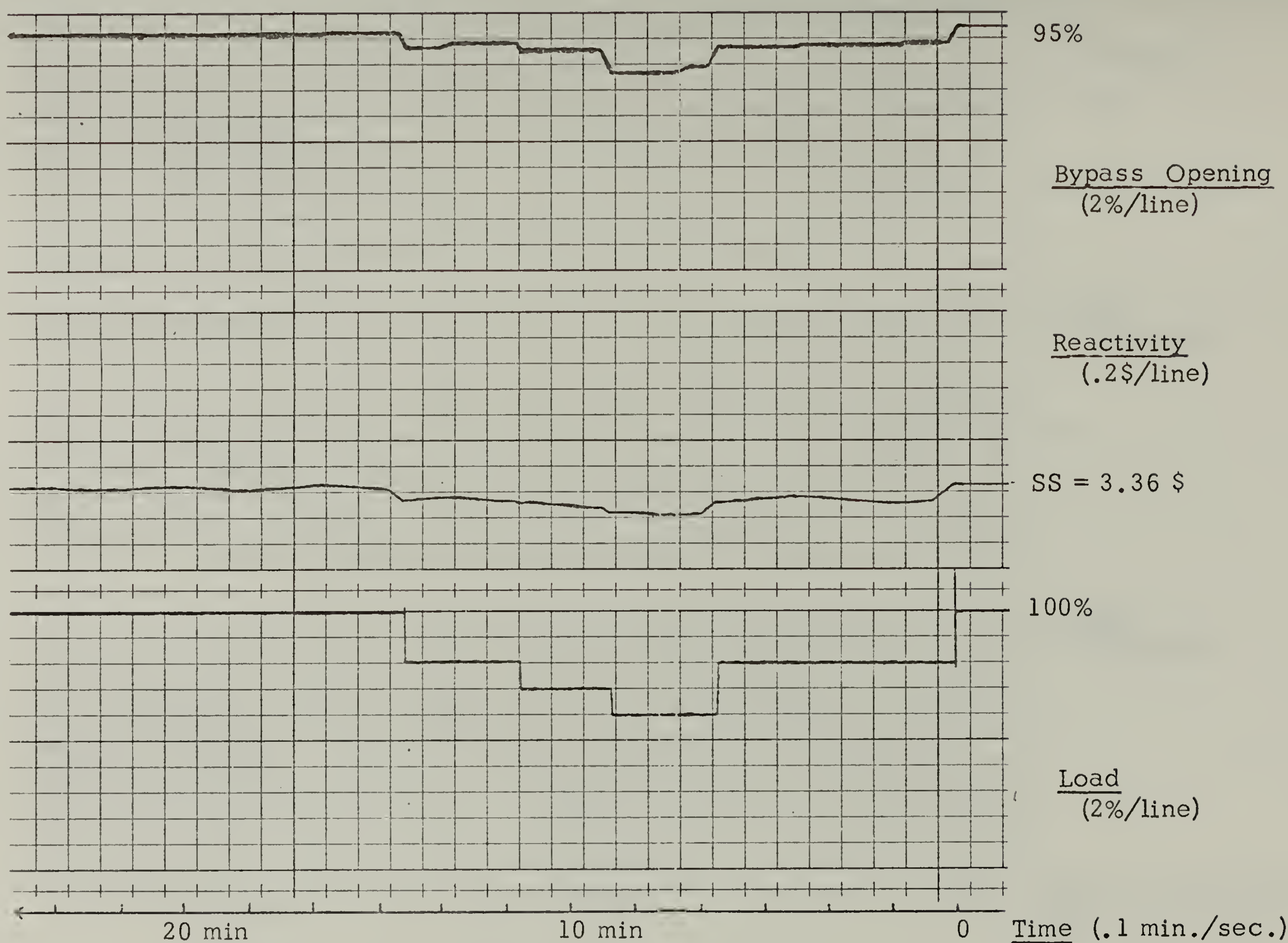


Fig. 20. Load changes (Small steps) with control action.

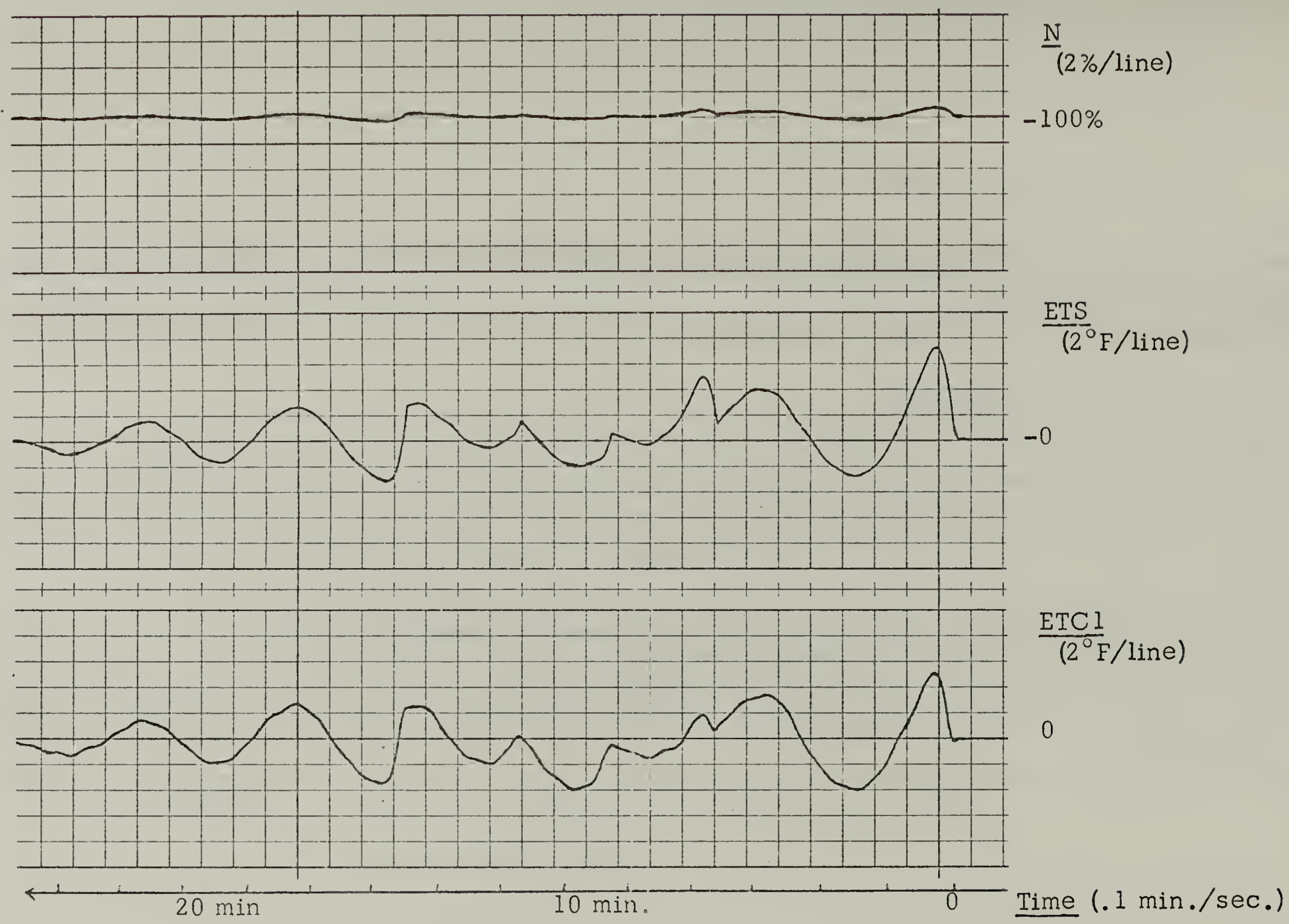

N
(2%/line)
-100%
ETS
(2°F/line)
-0
ETC1
(2°F/line)
0
20 min
10 min.
0
Time (.1 min./sec.)

Fig. 20a.

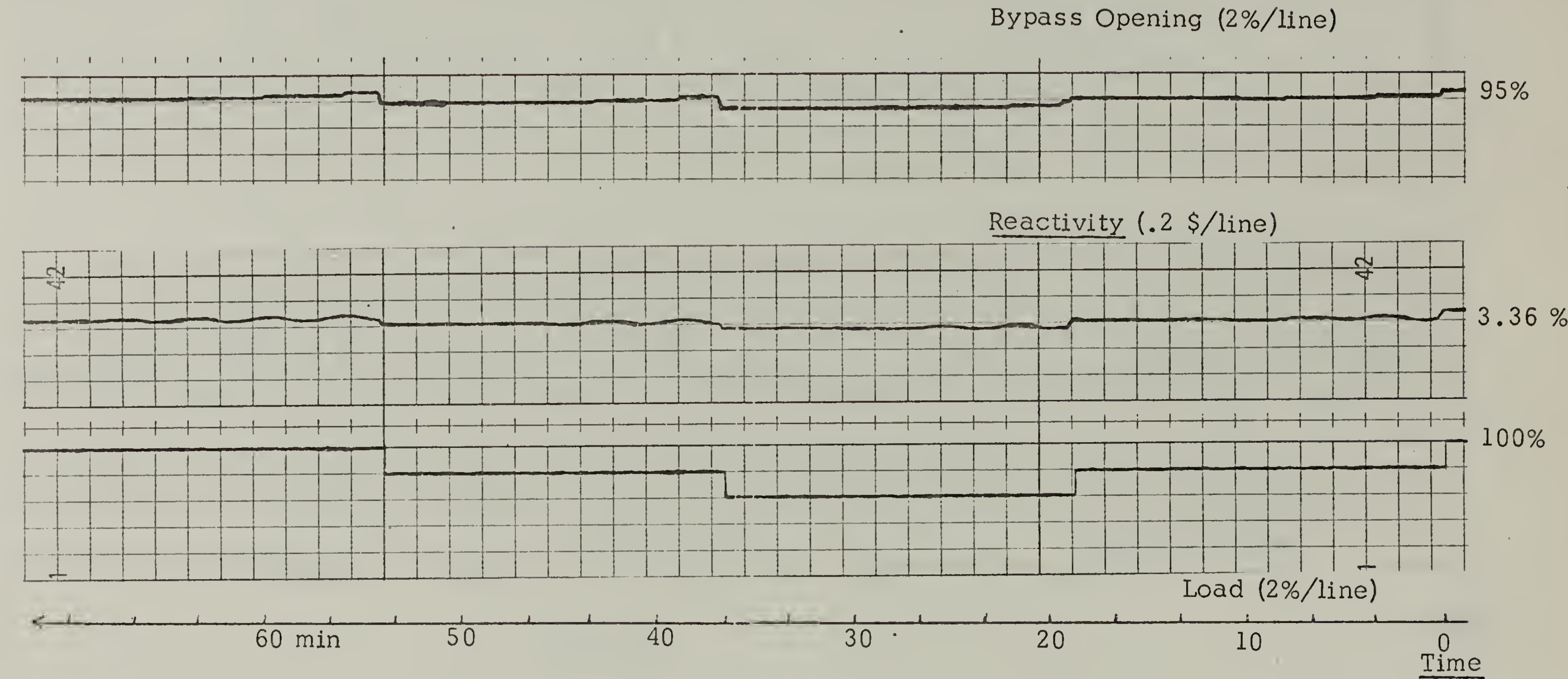


Fig. 21. Longterm control action.

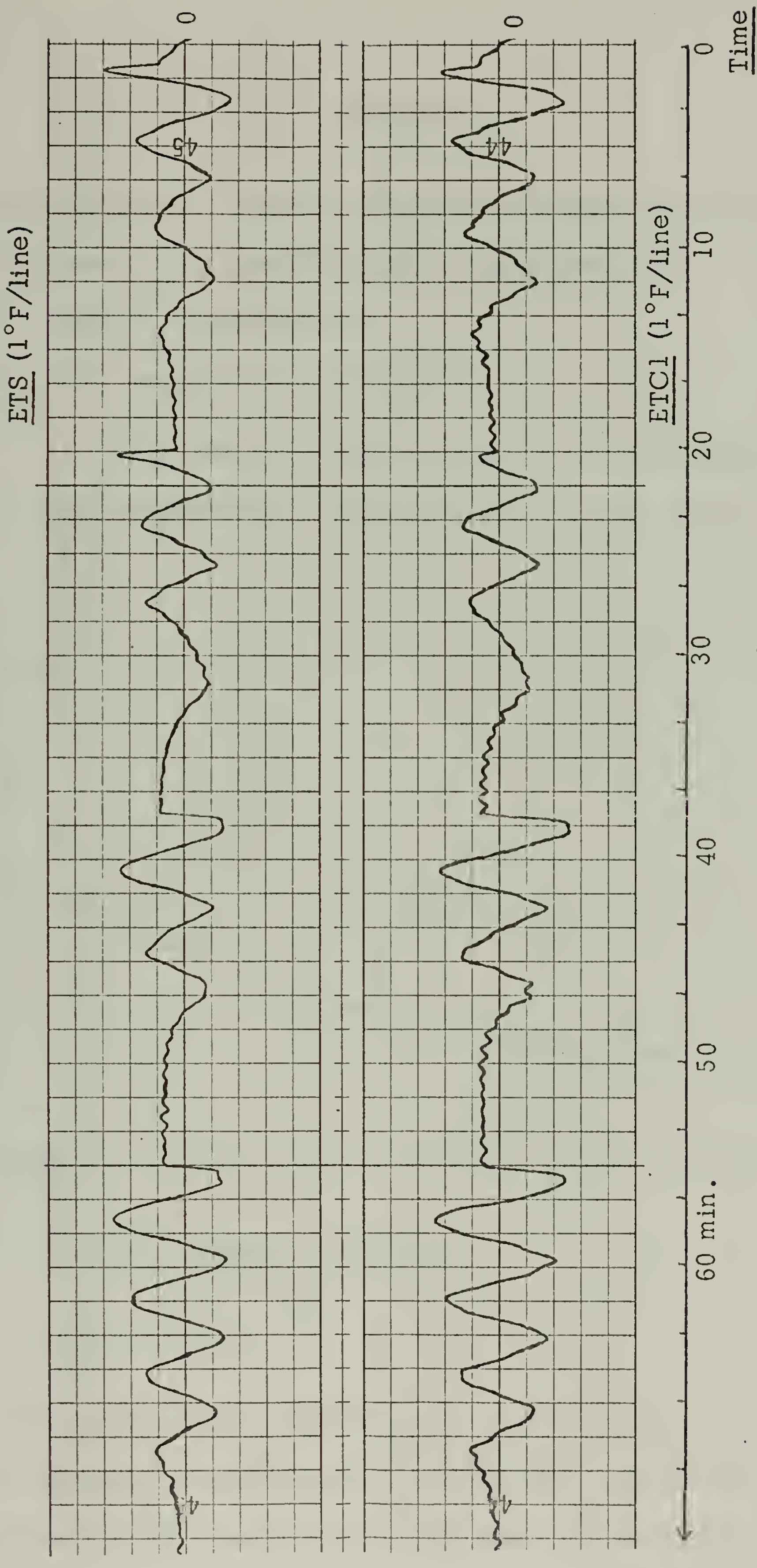


Fig. 21a.

APPENDIX A

A. CALCULATION OF THE REACTIVITY FEEDBACK COEFFICIENTS

The reactivity coefficients considered are

a) Doppler coefficient

b) Fuel expansion coefficient

a) The Doppler coefficient is a nonlinear function of the fuel temperature and is shown in Fig. 22.

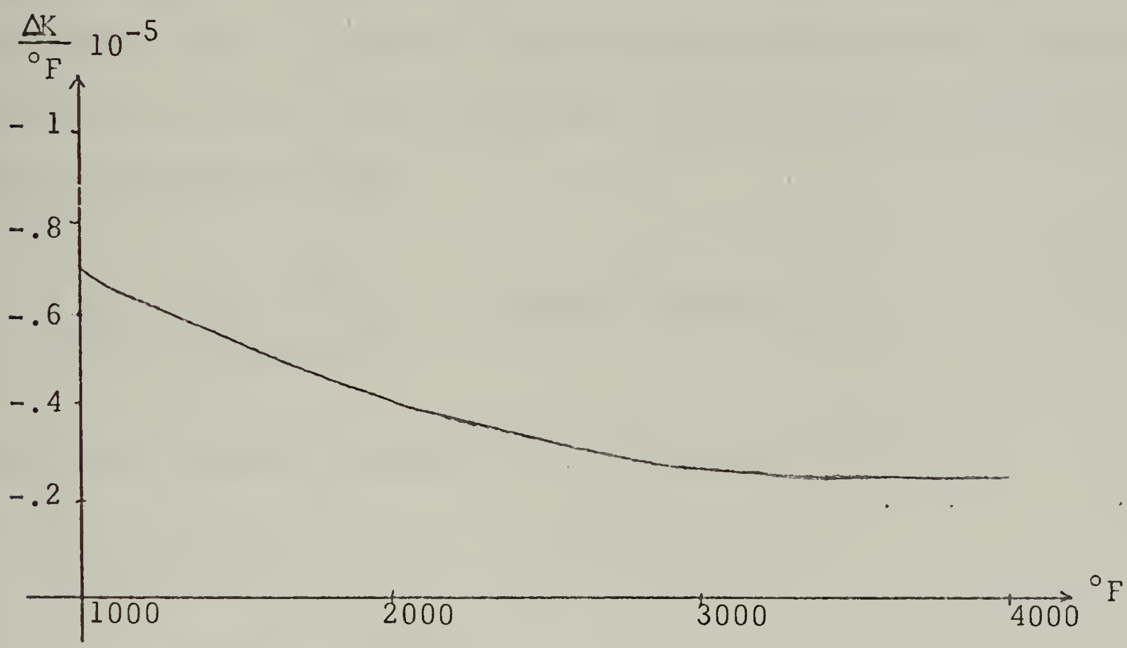


Fig. 22. Doppler coefficient.

Since the operating temperature of the reactor is at 2400°F an average doppler coefficient of $-.35\cdot 10^{-5}$ could be taken. It can be seen, that even at temperature variations of $\pm 400°$,

which have to be avoided in a fast reactor, the change in doppler coefficient is at most $\pm .5 \cdot 10^{-5}$. To account for a certain degrees of uncertainty a conservative numerical value of $-.3 \cdot 10^{-5}$ will be used. Changing this value to dollar units of reactivity with β taken as 29.88×10^{-4} the doppler coefficient is obtained as

$$K_D = \frac{-.3 \times 10^{-5}}{29.88 \times 10^{-4}} = -1.04 \times 10^{-3} \text{ dollars}$$

b) The fuel expansion coefficient is considerably smaller than the doppler coefficient and since its reliability for axial fuels is highly uncertain the conservative numerical value of $-1.0 \cdot 10^{-6}$ will be taken. The conversion into dollar units reactivity gives:

$$K_{EXP} = \frac{-1. \cdot 10^{-6}}{29.88 \times 10^{-4}} = -\ .34 \times 10^{-3} \text{ dollars}$$

The total feedback reactivity is therefore given as

$$K_F = K_D + K_{EX}$$

$$= -.00104 - .00034$$

$$= -.00138$$

$$= -.0014 \text{ dollars}$$

APPENDIX B

A. SOLUTION OF THE STEADY STATE, SECOND ORDER DIFFERENTIAL EQUATION FOR THE RADIAL HEAT FLOW IN A CYLINDRICAL FUEL ELEMENT

The heat balance equation is given as

$$Q\, 2\pi r\, dr\, L = Q_{r+dr} - Q_r \tag{B.1}$$

The differential heat quantities

$$Q_{r+dr} = Q_r + dQ_r = Q_r + \frac{dQ_r}{dr}\, dr \tag{b.2}$$

$$Q_r = -\, K_f\, A\, \frac{dT}{dr} = -\, K_f\, 2\pi r\, L\, \frac{dT}{dr} \tag{B.3}$$

equation (B.2) becomes now

$$Q_{r+dr} = -\, 2\pi\, L\, K_r\, \frac{dT}{dr} - 2\pi\, L\, K(r\, \frac{d^2T}{dr^2} + \frac{dT}{dr})\, dr \tag{B.4}$$

or

$$Q_F\, 2\pi r\, dr\, L = -\, 2\pi\, L\, \dot{K}(r\, \frac{d^2T}{dr^2} + \frac{dt}{dr})\, dr \tag{B.5}$$

which, after concellation and rearranging, may be written as

$$K\, \frac{d^2T}{dr^2} + \frac{K}{r}\, \frac{dT}{dr} + Q_F = 0 \tag{B.6}$$

This differential equation can be solved by standard methods, the solution is

$$T = -\, Q_F\, \frac{r^2}{4K} + C_1\, \ell n\, r + C_2 \tag{B.7}$$

The boundary conditions are

$$\left.\frac{dT}{dr}\right|_{r=0} = 0$$

$$T\Big|_{r=0} = T_c \qquad T\Big|_{r=R} = T_c$$

Applying these boundary conditions gives:

$$T_c - T_s = \frac{Q_F R^2}{4K}$$

Since

$$Q_R = \pi r^2 \, L \, Q_F \tag{B.8}$$

it follow that

$$Q_S = \pi R^2 \, L \, Q_F \tag{B.9}$$

or, combining (B.8) and (B.9)

$$Q_S = 4\pi \, K \, L(T_c - T_S) \tag{B.10}$$

Setting $2\pi \, R \, L = A$, the surface of the fuel element

$$Q_S = 2 \, K_f \, A \, \frac{T_c - T_S}{R} \tag{B.11}$$

Equation (B.11) holds for the region inside the fuel. For the cladding region K_{clad} would have to be used instead of K_f and for the region in the coolant $K_{coolant}$. Since average

temperature are used and in addition the individual thermal conductivities are considered constant, an average thermal conductivity will be taken and (B.3) may be written as

$$Q_r = - K \, 2\pi r \, L \, \frac{dT}{dr} \tag{B.12}$$

where r = the distance measured from the center of the fuel element.

T_c is taken as TF, the average fuel temperature and T_S as TAV, the average coolant temperature.

Equation (B.5) becomes then

$$Q_F = KA \, (TF - TAV) \tag{B.13}$$

APPENDIX C

A. CALCULATION OF THE GAIN COEFFICIENTS OF THE SYSTEMS DIFFERENTIAL EQUATIONS

The gain coefficients in the individual equations may be solved for by using the numerical values given for a specific plant. This would require a certain amount of engineering approximation, since exact values are not available for all quantities. Instead of following this approach, only given steady state temperature levels for 100% power ($\psi = 1$) at a bypass valve opening of 95% (X = .95) and given time constants were used. These values are [9]:

a) Steady state temperatures

TF = 2400°F

TH1 = 1100°F = TBI1

TC1 = 800°F = TB01

Th2 = 1050°F = TBI2

TC2 = 720°F = TB02

TS = 750°F

b) Time constants

T1 = 2 sec = T2

T3 = 4 sec = T4 = T6

T5 = 10 sec

T7 = .1 sec

Additional constants used [3]:

λ = .58

β = .002988

Setting these constants into the obtained dynamic equation these equations were "forced" into an accurate steady state solution by solving for the unknown gain coefficient in the steady state form of the differential equation ($\frac{dT}{dt} = 0$).

This procedure is demonstrated with one example:

The equation for heat transfer within the core was obtained as:

$$TF = - \frac{1}{T_1} TF + \frac{1}{T_1} TAV + A'N$$

which becomes in its steady state form

$$0 = - \frac{1}{2} (2400) + \frac{1}{2} (950) + A' (1)$$

and solving for A' gives

$$A' = 750$$

which is the desired coefficient for N. Using this approach for all equations individually leads to the system equations given in section II.

APPENDIX D

A. SCALING OF THE SYSTEM EQUATIONS

As mentioned in section III the actual equations must be scaled with respect to the maximum voltage levels of the analog computer. It is desirable to get maximum output values of the equation variables close to the computer maximum voltage level to maintain maximum accuracy in the solution of the differential equations. To be able to perform this scaling in an optimum way an exact knowledge of the maximum values of the plant variables is necessary. If these variables are not known exactly, optimum scaling is done by trial and error: a maximum value is assumed, the equations are scaled for a computer run and the output signal is observed. If this output signal is either to high or too low, the equations have to be rescaled.

The magnitude scaling procedure uses scaling coefficients which convert given plant variables with their individual dimensions to computer variables with the deminsion volt.

Taking the example of TAV it is written

$$TAV = SLTAV \cdot \overline{TAV}$$

where SLTAV = scaling coefficient for the plant variable TAV with dimension $\left[\frac{{}^\circ F}{V}\right]$

$\overline{TAV}$ = computer variable for average coolant temperature in core with dimension (V)

The analog computer used here (COMCOR Ci 5000) had a maximum voltage level of $\pm$ 100V. Assuming a maximum value of 1100°F for TAV the scaling coefficient is obtained as

$$\text{SLTAV} = \frac{\text{TAVX}}{\overline{\text{TAVX}}} = \frac{1100}{100} = 11 \left[\frac{°\text{F}}{\text{V}}\right]$$

Using this procedure the following numerical values for the individual scaling coefficient proved to be best suited:

SLD	=	.02
SLTF	=	30.
SLTAV	=	11.
SLTC1	=	10.
STBI1	=	12.5
SLTB2	=	9.5
STBI2	=	12.
SLTC2	=	9.5
SLTS	=	10.

The scaling procedure for a single dynamic equation proceeds as follows:

Taking equation (II.20)

$$\dot{\text{TAV}} = 5.3333\ \text{TAV} + .5 \quad \text{TF} + 4.8333\ \text{TC1}$$

Replacing the plant variables by computer variables gives

$$\text{SLTAV} \cdot \overline{\dot{\text{TAV}}} = -\ 5.3333 \cdot \text{SLTAV} \cdot \overline{\text{TAV}} + .5 \cdot \text{SLTF} \cdot \text{TF}$$
$$+\ 4.833 - \text{SLTC1} \cdot \overline{\text{TC1}}$$

Dividing through by SLTAV and using numerical values gives

$$\overline{\text{TAV}} = -\ 5.3333\ \overline{\text{TAV}} + 1.3636 \quad \overline{\text{TF}} + 4.3939 \quad \overline{\text{TC1}}$$

Using this procedure for all equations and steady state values gives the set of scaled equation given in III and the corresponding initial conditions for the integrators of the analog computer. These initial conditions were found to be

$\overline{TF}$ (0) = 80. (V)

$\overline{TAV}$ (0) = 86.3636 (V)

$\overline{TCL}$ (0) = 80 (V)

$\overline{TBI1}$ (0) = 88 (V)

$\overline{TB2}$ (0) = 93.1579 (V)

$\overline{TBI2}$ (0) = 87.5 (V)

$\overline{TC2}$ (0) = 75.7895 (V)

$\overline{TS}$ (0) = 75. (V)

The steady state control rod reactivity required is found to be 3.36 dollar which, after being scaled, corresponds to 33.6 (V).

APPENDIX E

A. ANALOG COMPUTER SETUP FOR CONTROLLER IMPLEMENTATION

It was shown in II, that several gain factors in the system dynamic equation were a function of the bypass valve opening X. Since the bypass is used as one of the controlling elements in the plant and therefore continually changes its numerical value, a way had to be found to continually change the gain factors which are functions of X. For the simulation without controller the gain factors were implemented as computer set potentiometers, which take a considerable amount of time to be set or adjusted. A continuous dynamic solution or simulation of the plant was therefore not possible with this setup.

The following method was used to get continuously changing gain factors and therefore a continuous simulation:

The potentiometers were replaced by electronic multipliers which had as input the to be multiplied variable (temperature) and the output of a trunkline which was controlled by the digital computer. Figure 23

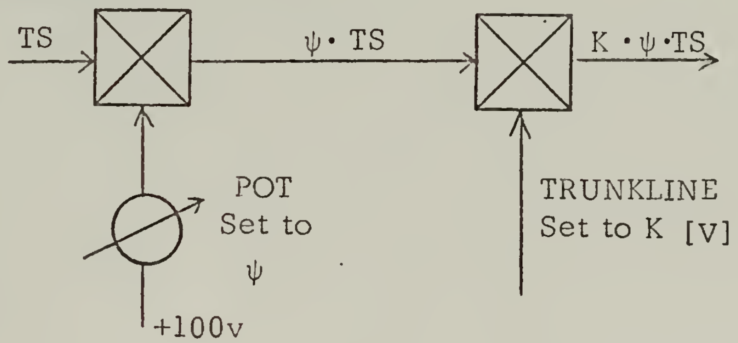


Fig. 23. Implementation of varying gain factors.

shows the analog implementation for the second gain factor in the differential equation for TS ($K \cdot \psi \cdot TS$). The voltage representing TS is multiplied by a voltage representing ψ ($0[V] < \psi < 100[V]$ corresponds to $0 < \psi < 100\%$ load). ψ was changed by a manually set potentiometer on the analog board. The output of this multiplier is fed into another multiplier with the trunkline as the second input. Each time (scan intervall = .1 sec) the controller changed X, it simultaneously calculated all dependent gain factors and adjusted the corresponding trunkline. Due to the electronic multiplication continuous adjustment of the gain factors without any timelag was thereby achieved.

Figure 24 shows the resulting analog computer setup for the plant part without the reactor. For more clarity of the graph no numerical values were set in and all initial condition inputs to the integrators with the corresponding potentiometers were left out. Figure 24 corresponds to the linear flowgraph of the plant system equation given in III.

Since there are no changing gain factors in the reactor part of the simulation Figure 13 in III is not changed.

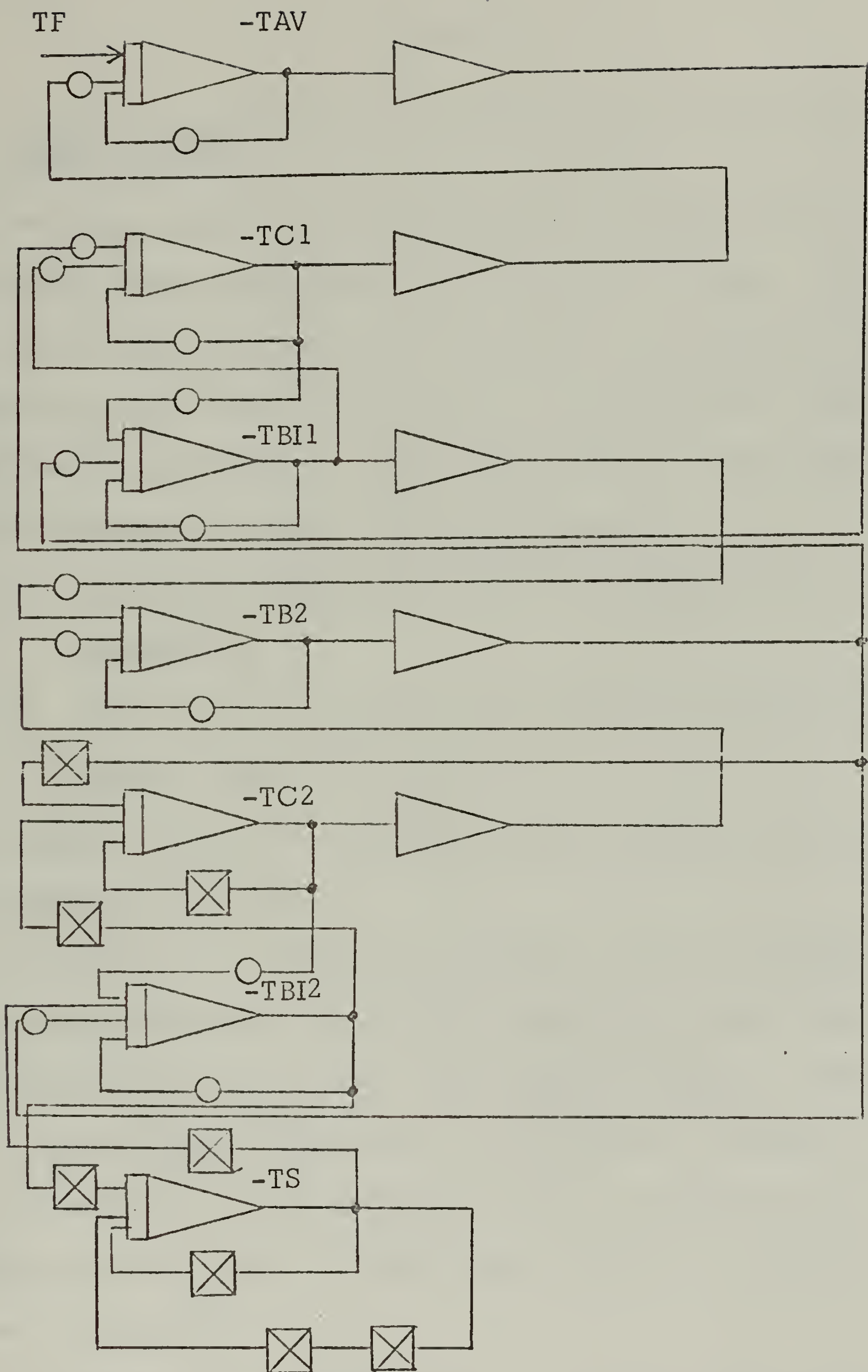


Fig. 24. Analog computer setup for plant.

APPENDIX F

A. CONTROL TRAJECTORY FOR PREPROGRAMMED POWER LEVEL CHANGE CONTROL

300 data points were obtained by changing the load over the whole range from 100% to 0% in small steps. For these runs the analog computer was in 1000 : 1 timescale mode, therefore the steady state error for a certain load was immediately available. (see Figure 27). Using hand set potentiometers voltages were supplied to

a) the analog computer which corresponded to control reactivity

b) the digital computer which corresponded to the bypass valve position.

The digital computer calculated the variable gain factors and adjusted the trunlines.

The "control reactivity voltage" and the "bypass voltage" were adjusted until the steady state error was zero. The obtained data points were then used to obtain, with the aid of a least square polonomial fit program, straight line approximations as precomputed control trajectory for load changes in the plant. These data points are shown in Figure 25 and Figure 26.

As may be seen from Figure 27, it is, with the controlling aids of this plant simulation possible to control TCI completely over the whole load range, TS can only be controlled over a load range from 100% load to about 20% load. The steady

state error for TS at zero load is about +80°F. This is not a restriction on the controllability of the plant.

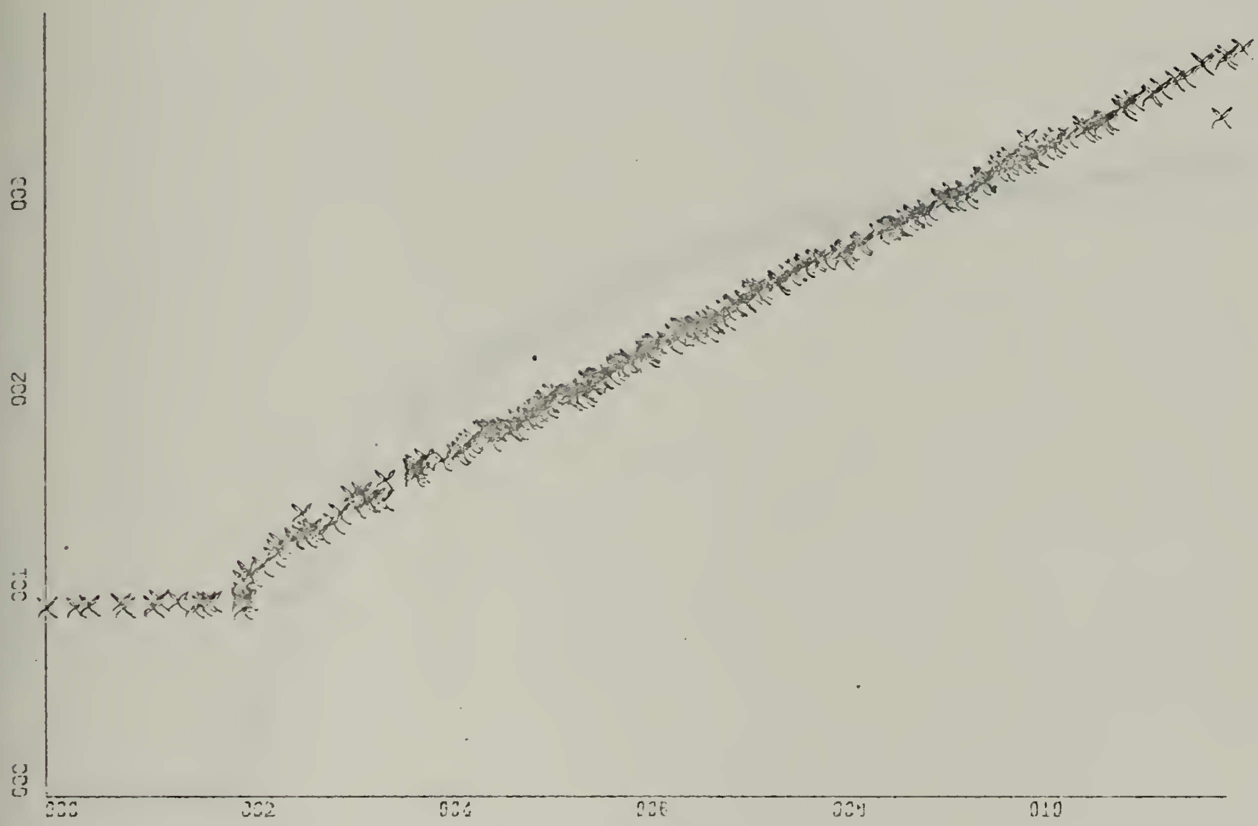


Fig. 25. Experimental data points.
Control Trajectory of reactivity
Scale X: 1 inch = 10% load
Y: 1 inch = dollar reactivity

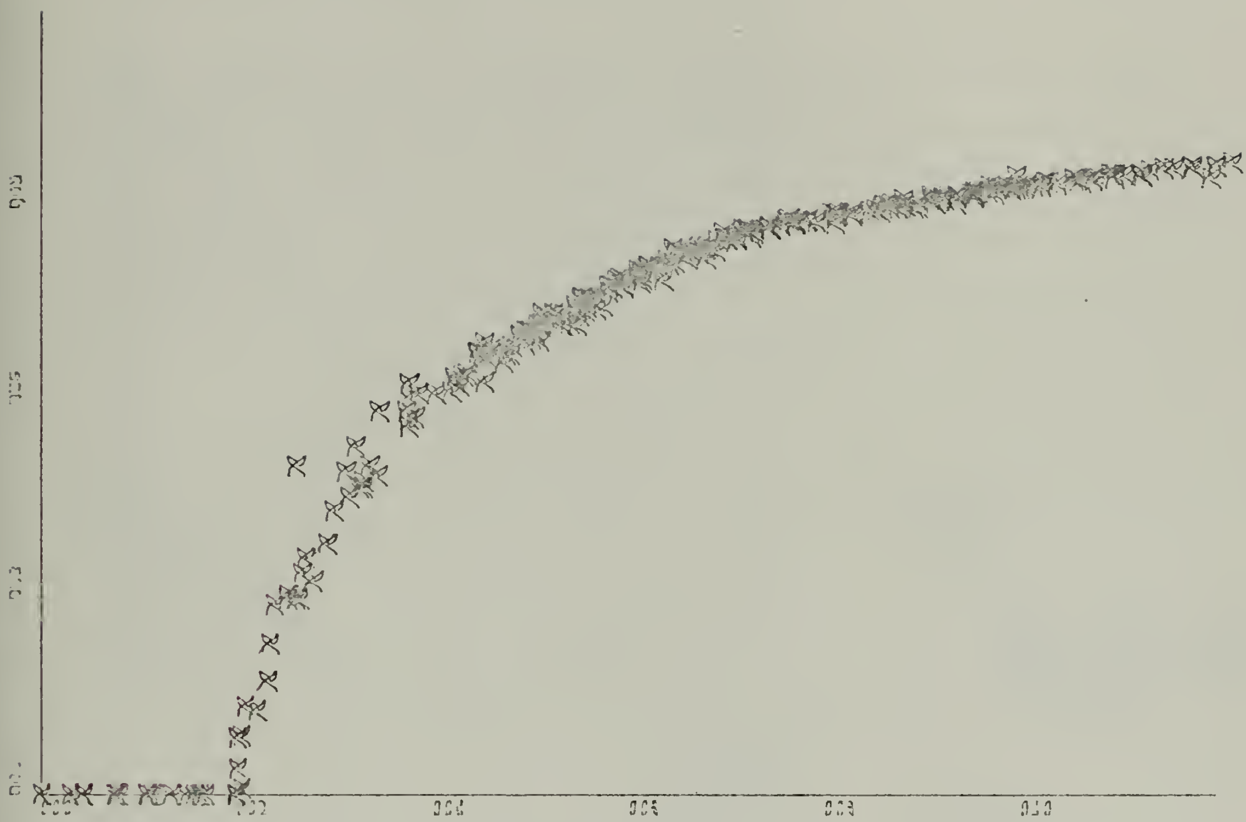


Fig. 26. Experimental Data points.

Control Trajectory of bypass opening

Scale: X: 1 inch = 10% load

Y: 1 inch = 10% valve opening

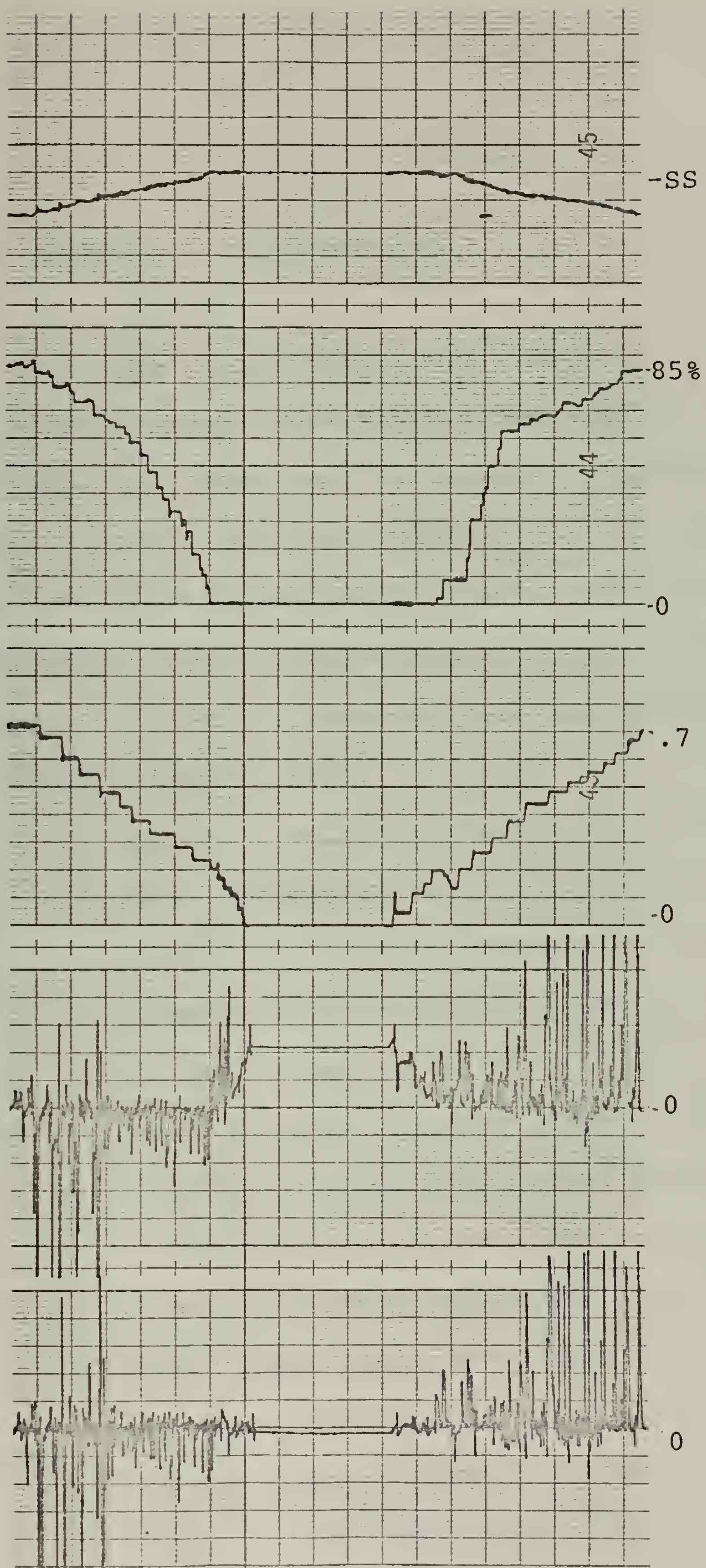


Fig. 27. Data Run for Load-Change.

APPENDIX G

A. DIGITAL CONTROL PROGRAM

1. General

The scan interval was chosen as .1 sec., i.e., the digital computer went through the designed control loop every .1 sec. and performed the necessary control action by scanning the assigned variables, performing the necessary calculations to get the derivatives or errors, and then going through all the logic steps, implemented as Fortran IF-statements. If control action was necessary it was performed by calling the following subroutines.

a) REACP: Increase reactivity at the rate of 2 cents/sec. Because of the scan interval the voltage of the trunkline which represented reactivity input was increased by an amount which corresponded to .2 cents/.1 sec. Inspite of being a step change the short time interval in which these changes were performed made the controlling action an almost continuous one. The time delay of an electric motor which would be used to perform this controlling action in a real plant, was neglected. This is justifiable in view of the short time constant of a motor with respect to the time constants of the plant.

b) REACM: Decrease reactivity at a rate of 2 cents/sec.

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b) REACM: Decrease reactivity at a rate of 2 cents/sec.

c) RACP and RACM: same as under a) and b) but with the rate divided by 10.

Subroutine REACP and REACM were called if controlling action was performed by preprogrammed controller. Subroutine RACP and RACM were called if controlling action was performed by small deviation controller.

d) VENTP: Open bypass valve at described rate (0 - 100% in 20 sec.). The subroutine changed the value of X, calculated the new gain factor and adjusted the corresponding trunklines to the electronic multipliers. The same statements made in a) with respect to continuous action and time constant hold also here.

e) VENTM: Decrease bypass valve opening at the described rate.

f) VETP and VETM: same as under d) and e) but with rate divided by 5.

Subroutine VENTP and VENTM were called by the preprogrammed controller subroutine VETP and VETM by the small deviation controller.

The digital controller program was divided in 3 parts:

a) Routing

b) Preprogrammed controller

c) Small deviation or steady state controller.

These 3 parts are described below.

2. <u>Routing</u>

The decision whether to go into the preprogrammed part of the controller or to the small deviation controller

was based on the rate of change of the load. For a load change of less than .2%/sec. the control action was performed by the small deviation controller. The flowchart of the routing part is given in Fig. 28.

3. Preprogrammed controller

The purpose of this controller was, to bring the controlling devices directly to their set points, i.e. to the points which were calculated by the straight line approximation - as a function of the load - to lie on the control trajectory. This controller performed its function without regard of the dynamics of the plant. The load was scanned, the set point calculated and the respective subprogram (Controlling action) called. Fig. 29 shows a flow chart of this part of the digital controller.

4. Small Deviation or Steady State Controller

As stated in III this part of the controller used proportional and derivative control. The decisions of the digital computer were based on the logic tables given as Table III and Table IV. The procedure used here is the same as in analog logic circuit, instead of writing expressions in Bolean algebra, Fortran IF-statements were written for the logic decisions of the digital computer.

Controlling action for change of reactivity was based on TAV and ETC1 (error in TC1). The logic table used is Table III.

Controlling action for change of bypass valve value was based on TB2 and ETS. The logic table used is Table IV.

With respect to earlier thoughts any decision made on the basis of Table III was weighted higher and if controlling action was required, Table IV was neglected, i.e. the controller tried first to bring ETCI to zero and keep it zero before ETS was controlled. This was done because of the dynamic of the plant. No logic scheme could be arrived at, which would have made combined control possible. It will be shown in section V, that the performance of this controller was very good. A flow diagram of this part of the digital controller is given in Figure 30.

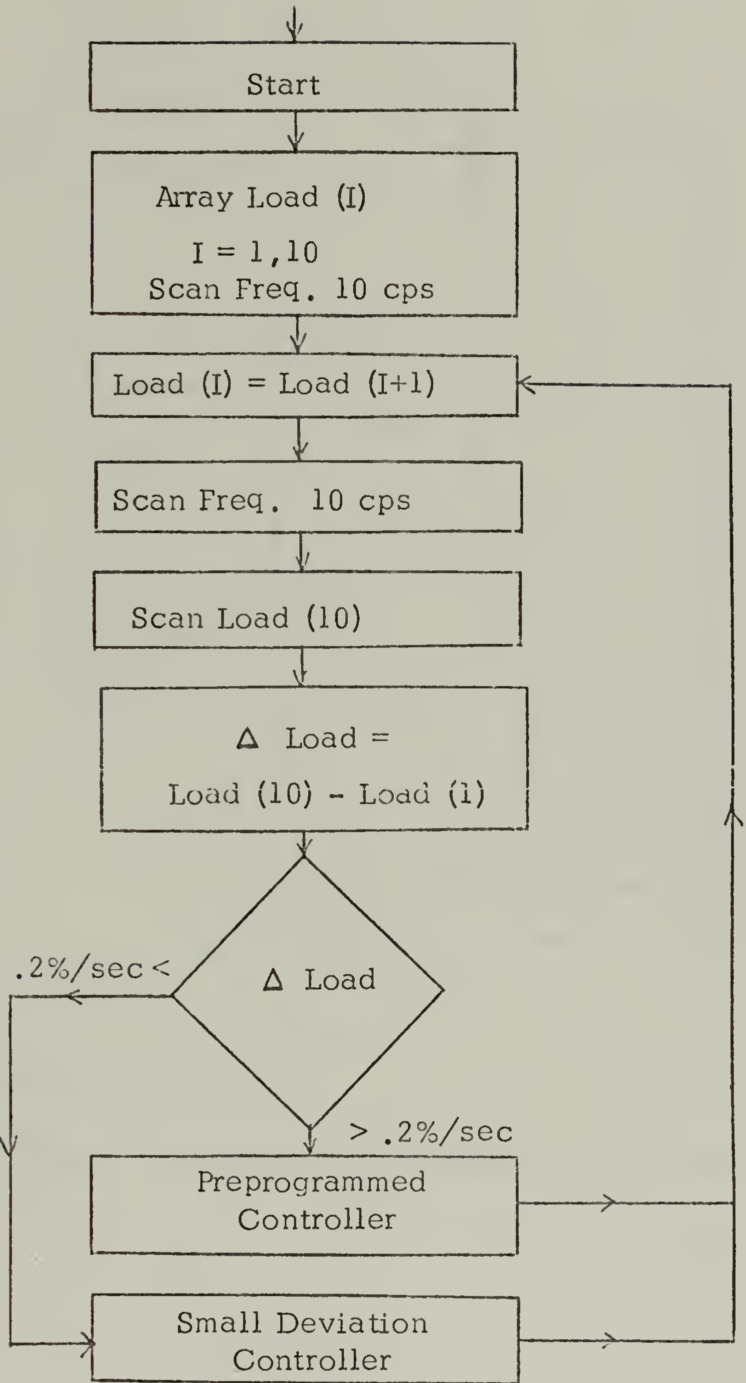

Fig. 28. Routing part of digital controller.

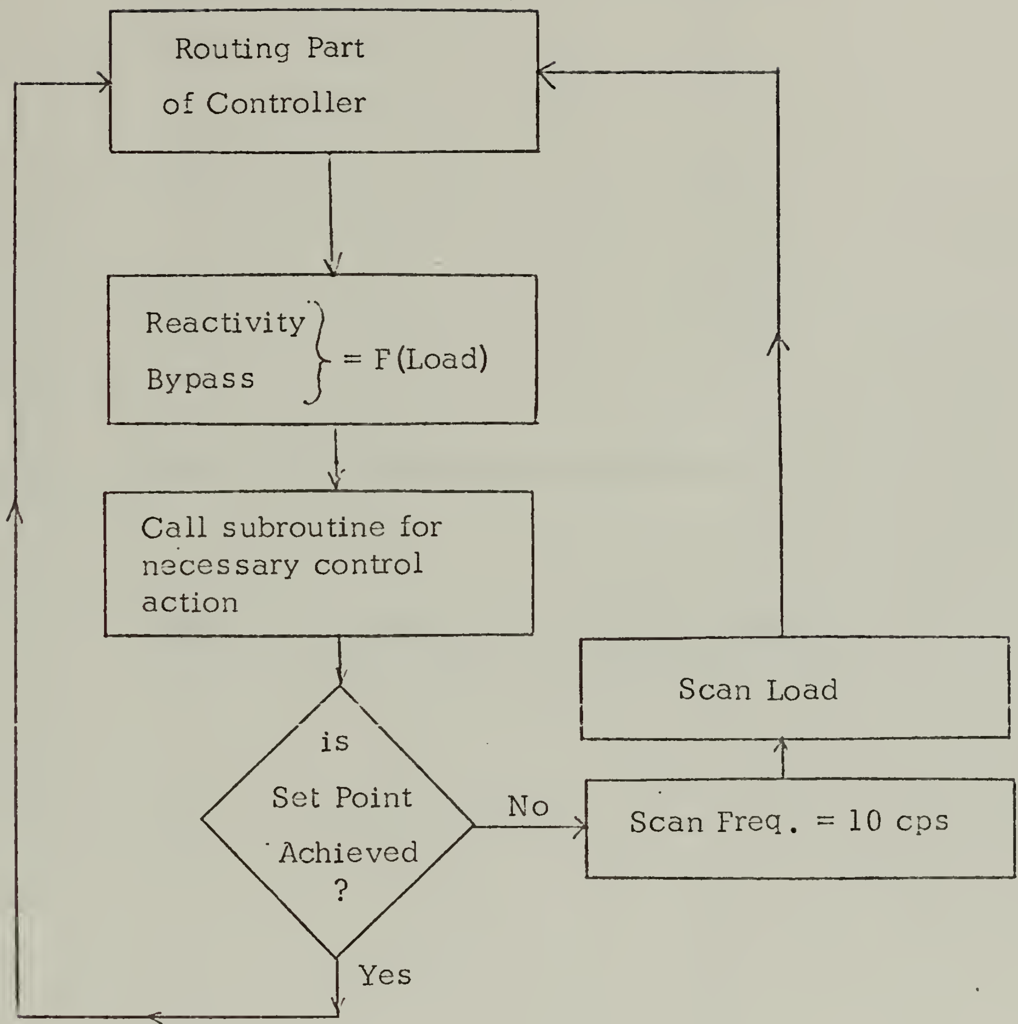

Fig. 29. Preprogrammed controller part of digital controller.

Logic Tables for Small Deviation Controller

TAV	ETC1	Reactiv.
0	0	./.
+	0	D
-	0	I
0	+	D
+	+	D
-	+	./.
0	-	I
+	-	./.
-	-	I

Table III. Reactivity control.

TB2	ETS	B. P. valve
0	0	./.
+	0	D
-	0	I
0	+	D
+	+	D
-	+	./.
0	-	I
+	-	./.
-	-	I

Table IV. Bypass valve control.

Symbols:

+	Error or Deriv. > 0
-	Error or Deriv. < 0
0	Error or Driv. = 0
D	Decrease
I	Increase
./.	No action

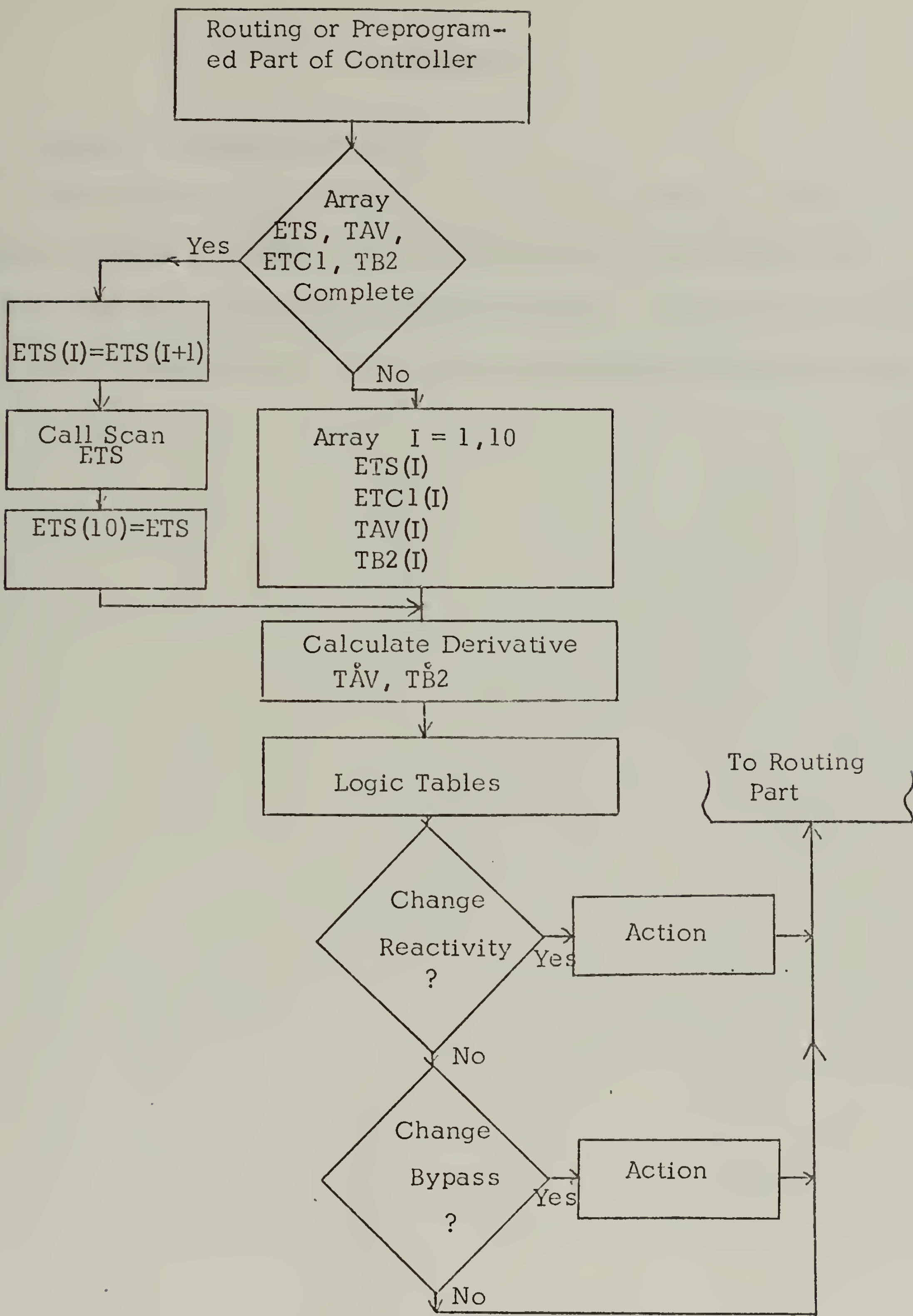

Fig. 30. Small deviation controller part of digital controller.

APPENDIX H

A. DIGITAL COMPUTER PROGRAM

The following pages are a copy of the digital computer program which was used for the complete Hybrid computer simulation and controller implementation. The program includes all parts described in the earlier sections and appendixes.

```
      INTEGER EAMP
      REAL  M000,M001,M002,M003,M004,M401,M402,M404,M405,N,NO
      NAMELIST R,R1,V,V1
      NAMELIST L
      DIMENSION PVAL(50)
      DIMENSION ALOAD(10)
      DIMENSION  ETS(10),ETC1(10),TAV(10),TB2(10)
C
C     GIVEN INITIAL CONDITION
C
      NO=1.
      DO=1.
      TFO=2400.
      TAVO=950.
      TC10=800.
      TBI10=1100.
      TB20=885.
      TBI20=1050.
      TC20=720.
      TSO=750.
C
C     GIVEN TIMECONSTANTS
C
      T1=2.
      T2=2.
      T3=4.
      T4=4.
      T5=10.
      T6=4.
      T7=.1
C
C     CHOOSEN VARIABLES
C
      ALMDA=.58
      PHI=1.
```

```
      X=.95
C
C     CALCULATED INITIAL CONDITIONS
C
      TB810=TC10
      TB10=(TBI10+TB810)/2.
      TH20=TBI20
      TB820=(TC20-(1.-X)*TH20)/X
      TB30=(TBI20+TB820)/2.
      AM1=(TBI10-TB10)/(TB10-TB20)
      AM2=(TBI20-TB30)/(TB30-TS0)*X
C
C     CALCULATION OF EQUATION COEFFICIENTS
C
      A=(TFO-TAVO)/(NO*T1)
      TO2=(TH20-TC20)/(TB10-TB20)*T7
      TO1=(2.*T2*(TAVO-TC10))/(TFO-TAVO)
        T21=1./((1./T2)+(2./TO1))
      T71=T7*(1.+AM1)
      T72=1./((AM1/(T7*(1.+AM1)))-(1./T7)-(2./TO2))
      T81=T6/(2.-X)
      T82=T6*(X+AM2)/(2.*X*AM2)
      T83=T6*(X+AM2)/(X*(X-AM2))
      T84=T6/(2.-2.*X)
      T52=T5*(X+AM2)/X
      T53=T5*(X+AM2)/(.4*PHI*X)
      T41=T4*(1.+AM1)/(1.-AM1)
      T42=T4*(1.+AM1)/(2.*AM1)
      B=1./T1
      C=1./T21
      D=1./T2
      E=2./TO1
      F=1./T3
      G=2./T3
      N=1./T72
```

```
      O=1./T71
      P=2./T02
      Q=1./T81
      R=1./T82
      S=1./T83
      T=1./T84
      U=1./T6
      V=2./T6
      Z=1./T52
      AA=1./T53
      AC=1./T4
      AD=1./T41
      AE=1./T42
      DERY1=ALMDA*(NO-DO)
      DERY2=-B*TFO+B*TAVO+A*NO
      DERY3=-C*TAVO+D*TFO+E*TC10
      DERY4=-AC*TC10+AD*TBI10+AE*TB20
         DERY5=-F*TBI10+G*TAVO-F*TC10
      DERY6=+N*TB20+O*TBI10+P*TC20
      DERY7=-Q*TC20+R*TSO+S*TBI20+T*TB20
      DERY8=-U*TBI20+V*TB20-U*TC20
      DERY9=-Z*TSO-AA*TSO+ Z*TBI20
C
C  WRITE SYSTEM DYNAMIC EQUATIAN
C
      WRITE(6,100) ALMDA
      WRITF(6,101)B,B,A
      WRITE(6,102) C,D,E
      WRITE(6,103) AC,AD,AE
      WRITF(6,104) F,G,F
      WRITE(6,105)N,O,P
      WRITE(6,106) Q,R,S,T
      WRITE(6,107) U,V,U
      WRITE(6,108) Z,AA,Z
      WRITF(6,109)DERY1,DERY2,DERY3,DERY4,DERY5,DERY6,DERY7,DERY8,DERY9
```

```
C
C   MAXIMUM VALUES ASSUMED
C
      AKTX=10.
      ANX=2.
      DX=2.
      TFX=3000.
      TAVX=1100.
      TC1X=1000.
      TBI1X=1250.
      TB2X=950.
      TBI2X=1200.
      TC2X= 950.
      TSX=1000.
C
C  .SCALING FACTORS
C
      SLAN=ANX/100.
      SLD=DX/100.
      SLTF=TFX/100.
      SLTAV=TAVX/100.
      SLTC1=TC1X/100.
      STBI1=TBI1X/100.
      SLTB2=TB2X/100.
      STBI2=TBI2X/100.
      SLTC2=TC2X/100.
      SLTS=TSX/100.
      SLAKT=AKTX/100.
C
C   SCALED COEFFICIENTS
C
      SA=B
      SB=B*SLTAV/SLTF
      SC=A*SLAN/SLTF
      SD=C
```

```
*
      SE=D*SLTF/SLTAV
      SF=E*SLTC1/SLTAV
      SG=AC
      SH=AD*STBI1/SLTC1
      SI=AF*SLTB2/SLTC1
      SJ=F
      SK=G*SLTAV/STBI1
      SL=F*SLTC1/STBI1
      SM=N
      SN=O*STBI1/SLTB2
      SO=P*SLTC2/SLTB2
      SP=Q
      SQ=R*SLTS/SLTC2
      SR=S*STBI2/SLTC2
      SS=T*SLTB2/SLTC2
      ST=U
      SU=V*SLTB2/STBI2
      SV=U*SLTC2/STBI2
      SW=Z
      SX=AA
      SY=Z *STBI2/SLTS
C
C  CALCULATE INITIAL CONDITIONS
C
      VNO=NO/SLAN
      VDO=DO/SLD
      VTFO=TFO/SLTF
      VTAVO=TAVO/SLTAV
      VTC10=TC10/SLTC1
      VTI10=TBI10/STBI1
      VTB20=TB20/SLTB2
      VTI20=TBI20/STBI2
      VTC20=TC20/SLTC2
      VTSO=TSO/SLTS
```

```
C
C   CALCULATE INITIAL DERIVATIVE
C
      VDEY1=ALMDA*(VNO-VDO)
      VDEY2=-SA*VTFO+SB*VTAVO+SC*VNO
      VDEY3=-SD*VTAVO+SE*VTFO+SF*VTC10
      VDEY4=-SG*VTC10+SH*VTI10+SI*VTB20
       VDEY5=-SJ*VTI10+SK*VTAVO-SL*VTC10
      VDEY6=+SM*VTB20+SN*VTI10+SO*VTC20
      VDEY7=-SP*VTC20+SQ*VTSO+SR*VTI20+SS*VTB20
      VDEY8=-ST*VTI20+SU*VTB20-SV*VTC20
      VDEY9=-SW*VTSO-SX*VTSO+SY*VTI20
C
C.  WRITE SCALED SYSTEM DYNAMIC EQUATIØN,
C   SCALING FACTØRS, INITIAL CØNDITIØNS
C
      WRITE(6,100)ALMDA
      WRITE(6,101)SA,SB,SC
      WRITE(6,102)SD,SE,SF
      WRITE(6,103)SG,SH,SI
      WRITE(6,104)SJ,SK,SL
      WRITE(6,106)SP,SQ,SR,SS
      WRITE(6,105)SM,SN,SO
      WRITE(6,107)ST,SU,SV
      WRITE(6,108)SW,SX,SY
      WRITE(6,110)VDEY1,VDEY2,VDEY3,VDEY4,VDEY5,VDEY6,VDEY7,VDEY8,VDEY9
      WRITE(6,115)
      WRITE(6,114)SLAN,SLD,SLTF,SLTAV,SLTC1,STBI1,SLTB2,STBI2,SLTC2,SLTS
     1,SLAKT
      WRITE(6,113)
      WRITE(6,112)VNO,VDO,VTFO,VTAVO,VTC10,VTI10,VTB20,VTI20,VTC20,VTSO
  100 FØRMAT(1H1,10X,'DDØT=',F4.2,'(N - D)',//)
  101 FØRMAT(10X,'TFDØT= -',F10.4,'TF +',F10.4,'TAV +',F10.4,'N',//)
  102 FØRMAT(10X,'TAVDØT= -',F10.4,'TAV +',F10.4,'TF +',F10.4,'TC1',//)
  103 FØRMAT(10X,'TCIDØT= -',F10.4,'TCI +',F10.4,'TBI1+',F10.4,'TB2',//
```

```
     1)
 104 FØRMAT(10X,'TBI1DØT= -',F10.4,'TBI1 +',F10.4,'TAV - ',F10.4,'TC1',
     1//)
 105 FØRMAT(10X,'TB2DØT= +',F10.4,'TB2 +',F10.4,'TBI1 +',F10.4,'TC2',//
     1)
 106 FØRMAT(10X,'TC2DØT= -',F10.4,'TC2 +',F10.4,'TS +',F10.4,'TBI2 +',F
     110.4,'TB2',//)
 107 FØRMAT(10X,'TBI2DØT = -',F10.4,'TBI2 +',F10.4,'TB2 -',F10.4,'TC2',
     1//)
 108 FØRMAT(10X,'TSDØT = -',F10.4,'TS -',F10.4,'TS +',F10.4,'TBI2',///)
 109 FØRMAT(10X,9F10.5)
 110 FØRMAT(     10X,9F10.4,//)
 112 FØRMAT(10X,10F10.4,////)
 113 FØRMAT(10X,'INITIAL CØNDITIØNS',//,16X,'VNO',6X,'VDO',5X,'VTFO',5X
     1,'VTAVO',5X,'VTC10',5X,'VTI10',5X,'VTB20',5X,'VTI20',5X,'VTC20',5X
     1,'VTSO')
 114 FØRMAT(10X,11F11.4,////)
 115 FØRMAT(16X,'SLAN',7X,'SLD',6X,'SLTF',6X,'SLTAV',6X,'SLTC1',6X,'STB
     1I1',6X,'SLTB2',6X,'STBI2',6X,'SLTC2',7X,'SLTS',6X, 'SLAKT')
C
C  ASSIGN PØTVALUES
C
      PVAL(1)=VDO*.01
      PVAL(2)=VTFO *.01
      PVAL(3)=VTAVO*.01
      PVAL(4)=VTC10*.01
      PVAL(5)=VTI10*.01
      PVAL(6)=VTB20*.01
      PVAL(7)=VTC20*.01
      PVAL(8)=VTI20*.01
      PVAL(9)=VTSO*.01
      PVAL(10)=ALMDA
      PVAL(11)=ALMDA
      PVAL(12)=SC
      PVAL(13)=SB
```

```
      PVAL(14)=SA
      PVAL(15)=SE*.1
      PVAL(16)=SF*.1
      PVAL(17)=SD*.1
      PVAL(18)=SI
      PVAL(19)=SH
      PVAL(20)=SG
      PVAL(21)=SK
      PVAL(22)=SL
      PVAL(23)=SJ
      PVAL(24)=SN*.1
      PVAL(25)=SO*.1
      PVAL(26)=SM*.1
      PVAL(27)=VTSO*.01
      PVAL(28)=VTB20*.01
      PVAL(29)=VTC10*.01
      PVAL(30)=SP*.1
      PVAL(31)=SV
      PVAL(32)=SU
      PVAL(33)=ST
      PVAL(34)=SY
      PVAL(35)=  SW +SX*PHI
      PVAL(36)=.1
      PVAL(37)=.0014*SLTF/SLAKT
      PVAL(38)=.0014*SLTF*.01*VTFO /SLAKT
      PVAL(39)=VDO/VNO *.1
      PVAL(40)=SLAKT
      PVAL(41)=SX
      CALL SETPOT(4HP053,PVAL(41))
      WRITE(6,10)(I,PVAL(I),I=1,41)
C
C  CALCULATE AMPLIFIER VALUES
C
      A001=-(100.*PVAL(1))/100.
      A003=-(100.*PVAL(2))/100.
```

```
A201=-A003
A005=-(100.*PVAL(3))/100.
A052=-A005
A013=-(100.*PVAL(4))/100.
A060=-A013
A076=1.
A011=-(100.*PVAL(5))/100.
A204=-A011
A007=-(100.*PVAL(6))/100.
A010=-A007
A025=-(100.*PVAL(7))/100.
A203=-A025
A027=-(100.*PVAL(8))/100.
A031=-(100.*PVAL(9))/100.
A024=0.
A014=0.
A030=0.
A056=-(100.*PVAL(38))/100.
A050=-(A056+PVAL(37)*A201)
A000=-((-100.*PVAL(39)/100.)+(A050*PVAL(40)*10.))
A006=SW
A202=-SY
A206=-SR
A016=-SQ
M003= A025 *.1*SP
M004=-(A007*SS)
M402=-(A027*SR)
M404=-(A031*SQ)
M405=A031* SW
M401=-(A027*SY)
M000=-((A001*PVAL(36)        )/A000)
M001=-A076*A031
M002=-M001*SX
```

*
*

```
C
C SET POTS AND GO RESET
C
      CALL SETPOT (4HP004,PVAL(1),4HP001,PVAL(10),4HP003,PVAL(11),4HP002
     1   ,PVAL(36),4HP021,PVAL(2),4HP005,PVAL(12),4HP055,PVAL(13),4HP006
     1   ,PVAL(14),4HP022,PVAL(3),4HP007,PVAL(15),4HP054,PVAL(16),4HP010
     1   ,PVAL(17),4HP044,PVAL(4),4HP020,PVAL(18),4HP013,PVAL(19),4HP015
     1   ,PVAL(20),4HP027,PVAL(5),4HP011,PVAL(21),4HP016,PVAL(22),4HP012
     1   ,PVAL(23),4HP026,PVAL(6),4HP014,PVAL(24),4HP032,PVAL(25),4HP023
     1,PVAL(26),4HP017,PVAL(7),4HP034,PVAL(27),4HP035,PVAL(28),4HP036
     1   ,PVAL(29),4HP030,PVAL(30),4HP024,PVAL(8),4HP031,PVAL(31),4HP040
     1,PVAL(32),4HP033,PVAL(33),4HP025,PVAL(9),4HP034,PVAL(9),4HP036
     1   ,PVAL(35),4HP052,PVAL(37),4HP050,PVAL(38),4HP051,PVAL(40),4HP00
     10  ,PVAL(39))
      CALL RESET(1000)
C
C   TEST ALL TRUNKLINES
C
      CALL DAC (1,.5,2,.5,3,.5,4,.5,5,.5,6,.5,7,.5,8,.5,9,.5,10,.5,11,.5
     1,12,.5)
      CALL SCAN (4HT420,T420,4HT421,T421,4HT422,T422,4HT423,T423,4HT424,
     1T424,4HT425,T425,4HT426,T426,4HT427,T427,4HT430,T430,4HT431,T431,4
     1HT432,T432,4HT433,T433)
      WRITE(101,225)T420,T421,T422,T423,T424,T425,T426,T427,T430,T431,T4
     132,T433
  225 FORMAT(10X,F10.4,/)
C
C   TRUNKLINE SETTINGS
C
      TSX=SX
      TSP=.1*SP
      TSW=-SW
      TSR = SR
      TSS = SS
      TSY = SY
```

```
      TSQ = SQ
      AKR=PVAL(38)
      CALL DAC (1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP)
      CALL DAC(9,AKR,10,X)
      L=0
C
C  SCAN ALL AMPLIFIERS AND COMPARE WITH CALCULATED VALUE
C
    1 CALL SCAN (4HA001,VA001,4HA003,VA003,4HA005,VA005,4HA013,VA013,
     14HA011,VA011,4HA007,VA007,4HA025,VA025,4HA027,VA027,4HA031,VA
     1031,4HA201,VA201,4HA052,VA052,4HA060,VA060,4HA204,VA204,4HA010,
     1VA010,4HA203,VA203,4HM001,VM001,4HA050,VA050,4HA000
     1,VA000,4HM000,VM000,4HA056,VA056)
      CALL SCAN (4HA206,VA206,4HA202,VA202,4HA006,VA006,4HA016,VA016,4HM
     1003,VM003,4HM004,VM004,4HM402,VM402,4HM401,VM401,4HM404,VM404,4HM4
     105,VM405,4HA030,VA030,4HA014,VA014,4HA024,VA024,4HM002,VM002)
      IF(L)226,226,227
C
C  WRITE CALCULATED AND SCANED AMPLIFIERVALUES
C
  226 WRITE(101,20)
      WRITE(6,20)
      WRITE(101,40) A001,VA001,A003,VA003,A005,VA005,A007,VA007,A011,VA0
     111,A013,VA013,A025,VA025,A027,VA027,A031,VA031,A201,VA201,A052,VA0
     152,A060,VA060,A204,VA204,A010,VA010,A203,VA203,
     1    A056,VA056,A050,VA050,A000,VA000,M000,VM000,A206,VA206,A202,VA2
     101,M404,VM404,M405,VM405,A030,VA030,A014,VA014,A024,VA024,M002,VM0
     102,A006,VA006,A016,VA016,M003,VM003,M004,VM004,M402,VM402,M401,VM4
     101,M001,VM001
      WRITE(6  ,40) A001,VA001,A003,VA003,A005,VA005,A007,VA007,A011,VA0
     111,A013,VA013,A025,VA025,A027,VA027,A031,VA031,A201,VA201,A052,VA0
     152,A060,VA060,A204,VA204,A010,VA010,A203,VA203,
     1    A056,VA056,A050,VA050,A000,VA000,M000,VM000,A206,VA206,A202,VA2
     102,A006,VA006,A016,VA016,M003,VM003,M004,VM004,M402,VM402,M401,VM4
     101,M404,VM404,M405,VM405,A030,VA030,A014,VA014,A024,VA024,M002,VM0
```

```
     101,M001,VM001
  227 CHE=1.
C
C  WRITE OCCURED ERRORS
C
      IF(ABSF(A001-VA001).GT..001) EAMP=4HA001 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A003-VA003).GT..001) EAMP=4HA003 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A005-VA005).GT..001) EAMP=4HA005 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A013-VA013).GT..001) EAMP=4HA013 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A011-VA011).GT..001) EAMP=4HA011 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A007-VA007).GT..001) EAMP=4HA007 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A025-VA025).GT..001) EAMP=4HA025 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A027-VA027).GT..001) EAMP=4HA027 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A031-VA031).GT..001) EAMP=4HA031 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A050-VA050).GT..001) EAMP=4HA050 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A056-VA056).GT..001) EAMP=4HA056 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A000-VA000).GT..001) EAMP=4HA000 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A201-VA201).GT..001) EAMP=4HA201 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A052-VA052).GT..001) EAMP=4HA052 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A204-VA204).GT..001) EAMP=4HA204 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A060-VA060).GT..001) EAMP=4HA060 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A010-VA010).GT..001) EAMP=4HA010 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A203-VA203).GT..001) EAMP=4HA203 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A206-VA206).GT..001) EAMP=4HA206 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A014-VA014).GT..001)EAMP=4HA014 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A024-VA024).GT..001)EAMP=4HA024 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A030-VA030).GT..001)EAMP=4HA030 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A202-VA202).GT..001)EAMP=4HA202 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A006-VA006).GT..001)EAMP=4HA006 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(A016-VA016).GT..001)EAMP=4HA016 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M001-VM001).GT..001)EAMP=4HM001;CALL WRITE (EAMP,CHE)
      IF(ABSF(M002-VM002).GT..001)EAMP=4HM002 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M000-VM000).GT..001) EAMP=4HM000 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M003-VM003).GT..001)EAMP=4HM003 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M004-VM004).GT..001)EAMP=4HM004 ; CALL WRITE(EAMP,CHE)
```

```
      IF(ABSF(M402-VM402).GT..001)EAMP=4HM402 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M401-VM401).GT..001)EAMP=4HM401 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M404-VM404).GT..001)EAMP=4HM404 ; CALL WRITE(EAMP,CHE)
      IF(ABSF(M405-VM405).GT..001)EAMP=4HM405 ; CALL WRITE(EAMP,CHE)
C
C  SCAN ALL TRUNKLINES AND COMPARE WITH CALCULATED VALUE
C
      CALL SCAN(4HT420,TSX,4HT421,TSS,4HT422,TSR,4HT423,TSY,4HT424,
     1TSW,4HT425,TSQ,4HT427,TSP,4HT430,AKR,4HT431,X1)
C
C  WRITE OCCURED ERRORS
C
      IF(ABSF(X1-X).GT..001)EAMP=4HT431;CALL WRITE(EAMP,CHE)
      IF(ABSF(AKR-PVAL(38)).GT..001)EAMP=4HT430;CALL WRITE(EAMP,CHE)
      IF(ABSF(TSX-SX).GT..001) EAMP=4HT420 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSS-SS).GT..001) EAMP=4HT421 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSR-SR).GT..001) EAMP=4HT422 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSY-SY).GT..001) EAMP=4HT423 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSW+SW).GT..001) EAMP=4HT424 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSQ-SQ).GT..001) EAMP=4HT425 ; CALL WRITE (EAMP,CHE)
      IF(ABSF(TSP -.1*SP).GT..001)EAMP=4HT427 ; CALL WRITE(EAMP,CHE)
      IF(CHE)50,50,400
 50   CALL MANUAL(2)
      L=1
      INPUT (101).
      IF(L.EQ.2) GOTO 70
      GOTO 1
 400  WRITE (101,60)
  70  CALL MANUAL(1)
C
C  BEGIN OF CONTROLER
C
      CALL COMPUTE
 224  CALL WRITECLOCK (0)
      K=0
```

```
      M=0
      R=.00002
      R1=.000002
      V=.0005
      V1=.0001
      K0NT=0
      K0NT1=0
      D0 525 I=1,10
       ETC1(I)=.0
      ETS(I)=.0
      TAV(I)=.8636
      T32(I)=.9315
  525 C0NTINUE
      CALL STARTCL0CK
C
C  R0UTING PART 0F C0NTR0LER
C
      D0 520 I=1,10
  524 CALL READCL0CK (ITIME)
      IF (ITIME/100*100.NE. ITIME) G0T0 524
      CALL SCAN (4HA076,PHI)
      AL0AD(I)=PHI
  520 C0NTINUE
  501 CALL READCL0CK (ITIME)
      IF (ITIME/100*100.NE.ITIME) G0T0501
      CALL SCAN (4HA076,PHI,4HA064,ST0P)
      IF(ST0P-.5)505,505,402
  505 D0 521 I=1,9
      AL0AD(I)=AL0AD(I+1)
  521 C0NTINUE
      AL0AD(10)=PHI
      DL0AD=ABSF(AL0AD(10)-AL0AD(1))
      IF(DL0AD.LT..002)G0T0 523
*
*
```

```
C
C  PREPROGRAMMED PART OF CONTROLER
C
      GOTO 507
  506 CALL READCLOCK (ITIME)
      IF(ITIME/100*100.NE.ITIME) GOTO 506
      CALL SCAN(4HA076,PHI,4HA064,STOP)
      IF(STOP.GT..5) GOTO 402
  507 AMX=AM2/X
      AKSET=AKR
      XSET=X
      A1SET=AKSET+.0001
      X1SET=XSET+.0003
      A2SET=AKSET-.0001
      X2SET=XSET-.0003
C
C  CONTROL TRAJECTORY
C
      A=.394+.6566*PHI
      B=.713+.21 *PHI
      XFIN=-.173+1.68*PHI
      AKFIN=-(-.07-.25 *PHI)
      IF(PHI.GT..55)XFIN=A
      IF(PHI.GT..72)XFIN=B
      IF(XFIN.LT..0) XFIN=.0
      IF(XFIN.GT.1.) XFIN=.9999
      KONT=0
      IF(X1SET.LT.XFIN)CALL VENTP(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V)
      IF(X2SET.GT.XFIN)CALL VENTM(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V)
      IF(A1SET.LT.AKFIN)CALL REACP(SLAKT,AKR,KONT1,R)
      IF(A2SET.GT.AKFIN)CALL REACM (SLAKT,AKR,KONT1,R)
      IF(X1SET.LT.XFIN)K=0
      IF(X1SET.LT.XFIN)KONT=1
      IF(X2SET.GT.XFIN)K=0
      IF(X2SET.GT.XFIN)KONT=1
```

```
      IF(A1SET.LT.AKFIN)K=0
      IF(A1SET.LT.AKFIN)K0NT=1
      IF(A2SET.GT.AKFIN)K=0
      IF(A2SET.GT.AKFIN)K0NT=1
      IF(K0NT.EQ.1) G0T0 506
      IF(K.EQ.50) G0T0 210
  503 CALL READCL0CK(ITIME)
      IF(ITIME/100*100.NE.ITIME) G0T0 503
      K=K+1
      IF(K.LT.50) G0T0 503
C
G  SMALL DEVIATION PART 0F C0NTR0LER
C
  200 D0 260 I=1,10
      IF(ITIME/100 *100 .NE.ITIME)G0T0200
      CALL SCAN (4HA030,STS,4HA024,STC,4HA010,SB2,4HA052,SAV)
      ETS(I)=STS
      ETC1(I)=STC
      TAV(I)=SAV
      TB2(I)=SB2
  260 C0NTINUE
      G0T0 220
  523 C0NTINUE
  210 D0 270 I=1,9
      ETS(I)=ETS(I+1)
      ETC1(I)=ETC1(I+1)
      TAV(I)=TAV(I+1)
      TB2(I)=TB2(I+1)
  270 C0NTINUE
      CALL SCAN (4HA030,STS,4HA024,STC,4HA010,SB2,4HA052,SAV)
      ETS(10)=STS
      ETC1(10)=STC
      TAV(10)=SAV
      TB2(10)=SB2
  220 I1=0
```

```
      I3=0
      ID4=0
      ID5=0
      KØNT1=0
C
C  ASSIGN LØGIC SYMBØLS
C
      IF (ETS(10).GT..005)  I1=1
      IF( ETS(10).LT.-.005) I1=-1
      IF (ETC1(10).LT.-.005) I3=-1
      IF (ETC1(10).GT..005)  I3=1
      IF ((TAV(10)-TAV(1)).LT.-.001) ID4=-1
      IF ((TAV(10)-TAV(1)).GT..001) ID4=1
      IF ((TB2(10)-TB2(1)).GT..005) ID5=1
      IF ((TB2(10)-TB2(1)).LT.-.005) ID5=-1
C
C  GØ THRØUGH LØGIC TABLES
C
      IF(  I3.EQ.0   .AND.      ID4.EQ.1
     1     .ØR.
     1     I3.EQ.1   .AND.      ID4.EQ.0
     1     .ØR.
     1     I3.EQ.1   .AND.      ID4.EQ.1   )
     1CALL RACM (SLAKT,AKR,KØNT1,R1)
      IF( I3.EQ.0    .AND.      ID4.EQ.-1
     1     .ØR.
     1     I3.EQ.-1  .AND.      ID4.EQ.0
     1     .ØR.
     1     I3.EQ.-1  .AND.      ID4.EQ.-1 )
     1CALL RACP (SLAKT,AKR,KØNT1,R1)
      IF(KØNT1.EQ.1) M=0
      M=M+1
      IF(KØNT1.EQ.1)  GØTØ 501
      IF(M.LT.20) GØTØ 501
      IF( I1.EQ.0    .AND.      ID5.EQ.1
```

```
     1     .OR.
     1     I1.EQ.1    .AND.     ID5.EQ.0
     1     .OR.
     1     I1.EQ.1    .AND.     ID5.EQ.1  )
     1CALL VETM(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V1)
      IF( I1.EQ.0    .AND.     ID5.EQ.-1
     1     .OR.
     1     I1.EQ.-1   .AND.     ID5.EQ.0
     1     .OR.
     1     I1.EQ.-1   .AND.     ID5.EQ.-1 )
     1CALL VETP(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V1)
      GOTO 501
C
C. EXIT.  POSSIBILITY TO RUN AGAIN AFTER BRINGING
C         SIMULATION SETUP BACK TO 100 PERCENT LOAD
C         STEADY STATE CONDITION
C
  402 CALL HOLD
      CALL STOPCLOCK
      CALL MANUAL(4)
      TSX=SX
      TSS = SS
      TSR = SR
      TSY = SY
      TSW=-SW
      TSP=.1*SP
      TSQ = SQ
      CALL DAC (1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP)
      X=.95
      AKR=PVAL(38)
      CALL DAC(9,AKR,10,X)
      INPUT (101)
      CALL WRITECLOCK (0)
      CALL STARTCLOCK
      GOTO 501
```

```
60 FØRMAT(10X,'ALL AMPLIFIERS Ø.K.,GØ')
10 FØRMAT(5X,'PVAL(',I2,'),=',F6.4,/)
20 FØRMAT ('CALCUL.VAL.',3X,'READINGS')
40 FØRMAT(2F10.4)
   END
```

```
      SUBRØUTINE RACP(SLAKT,AKR,KØNT1,R1)
C
C  INCREASE REACTIVITY AND ADJUST TRUNKLINES
C  RATE FØR SMALL DEVIATIØN CØNTRØLER
C
      KØNT1=1
      AKR=(AKR+(R1/SLAKT))
      CALL DAC(9,AKR)
      RETURN
      END
```

```
      SUBROUTINE RACM(SLAKT,AKR,KONT1,R1)
C
C  DECREASE REACTIVITY AND ADJUST TRUNKLINES
C  RATE FOR SMALL DEVIATION CONTROLER
C
      KONT1=1
      AKR=(AKR-(R1/SLAKT))
      CALL DAC(9,AKR)
      RETURN
      END
```

```
      SUBRØUTINE VETP (T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V1)
C
C  INCREASE BYPASS VALVEØPENING, CALCULATE GAIN FACTØRS
C  AND ADJUST TRUNKLINES
C  RATE FØR SMALL DEVIATIØN CØNTRØLER
C
      X=X+V1
      IF(X.GE.1.) X=.9999
      AM3=AMX*X
      TSP=.1*(1./(T6/(2.-X)))
      TSS=1./(T6/(2.-2.*X))*SLTB2/SLTC2
      TSR=STBI2/SLTC2 *1./(T6*(X+AM3)/(X*(X-AM3)))
      TSW=-1./(T5*(X+AM3)/X)
      TSQ=SLTS/SLTC2 *1./(T6*(X+AM3)/(2.*X*AM3))
      TSX=1./(T5*(X+AM3)/(.4*X))
      TSY=STBI2/SLTS * 1./(T5*(X+AM3)/X)
      CALL DAC(1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP,10,X)
      RETURN
      END
```

```
      SUBROUTINE VETM (T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V1)
C
C  DECREASE BYPASS VALVEOPENING, CALCULATE GAIN FACTORS
C  AND ADJUST TRUNKLINES
C  RATE FOR SMALL DEVIATION CONTROLER
C
      X=X-V1
      IF(X.GE.1.) X=.9999
      AM3=AMX*X
      TSP=.1*(1./(T6/(2.-X)))
      TSS=1./(T6/(2.-2.*X))*SLTB2/SLTC2
      TSR=STBI2/SLTC2 *1./(T6*(X+AM3)/(X*(X-AM3)))
      TSW=-1./(T5*(X+AM3)/X)
      TSQ=SLTS/SLTC2 *1./(T6*(X+AM3)/(2.*X*AM3))
      TSX=1./(T5*(X+AM3)/(.4*X))
      TSY=STBI2/SLTS * 1./(T5*(X+AM3)/X)
      CALL DAC(1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP,10,X)
      RETURN
      END
```

```
      SUBRØUTINE WRITE(EAMP,CHE)
C
C  WRITE ERRØRS
C
      CHE=0.
  200 WRITE(101,30) EAMP
   30 FØRMAT(10X,'ERRØR ØN',2X,A4)
      RETURN
      END
```

```
      SUBROUTINE REACP  (SLAKT,AKR,KONT1,R)
C
C  INCREASE REACTIVITY AND ADJUST TRUNKLINES
C  RATE FOR PREPROGRAMMED CONTROLER
C
      KONT1=1
      AKR=AKR+(R/SLAKT)
      CALL DAC(9,AKR)
      RETURN
      END
```

```
      SUBRØUTINE REACM  (SLAKT,AKR,KØNT1,R)
C
C  DECREASE REACTIVITY AND ADJUST TRUNKLINES
C  RATE FØR PREPRØGRAMMED CØNTRØLER
C
      KØNT1=1
      AKR=AKR-(R/SLAKT)
      CALL DAC(9,AKR)
      RETURN
      END
```

```
      SUBRØUTINE VENTP(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V)
C
C  INCREASE BYPASS VALVEØPENING, CALCULATE GAIN FACTØRS
C  AND ADJUST TRUNKLINES
C  RATE FØR PREPRØGRAMMED CØNTRØLER
C
      X=X+V
      IF(X.GE.1.) X=.9999
      AM3=AMX*X
      TSP=.1*(1./(T6/(2.-X)))
      TSS=1./(T6/(2.-2.*X))*SLTB2/SLTC2
      TSR=STBI2/SLTC2 *1./(T6*(X+AM3)/(X*(X-AM3)))
      TSW=-1./(T5*(X+AM3)/X)
      TSQ=SLTS/SLTC2 *1./(T6*(X+AM3)/(2.*X*AM3))
      TSX=1./(T5*(X+AM3)/(.4*X))
      TSY=STBI2/SLTS * 1./(T5*(X+AM3)/X)
      CALL DAC(1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP,10,X)
      RETURN
      END
```

```
      SUBRØUTINE VENTM(T6,X,SLTB2,SLTC2,STBI2,SLTS,T5,AMX,V)
C
C  DECREASE BYPASS VALVEØPENING, CALCULATE GAIN FACTØRS
C  AND ADJUST TRUNKLINES
C  RATE FØR PREPRØGRAMMED CØNTRØLER
C
      X=X-V
      IF(X.GE.1.) X=.9999
      AM3=AMX*X
      TSP=.1*(1./(T6/(2.-X)))
      TSS=1./(T6/(2.-2.*X))*SLTB2/SLTC2
      TSR=STBI2/SLTC2 *1./(T6*(X+AM3)/(X*(X-AM3)))
      TSW=-1./(T5*(X+AM3)/X)
      TSQ=SLTS/SLTC2 *1./(T6*(X+AM3)/(2.*X*AM3))
      TSX=1./(T5*(X+AM3)/(.4*X))
      TSY=STBI2/SLTS * 1./(T5*(X+AM3)/X)
      CALL DAC(1,TSX,2,TSS,3,TSR,4,TSY,5,TSW,6,TSQ,8,TSP,10,X)
      RETURN
      END
```

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13. ABSTRACT

The dynamic equations for a Liquid Metal Fast Breeder Nuclear Reactor (LMFBR) Power Plant are derived. These nonlinear differential equations with typical design values for the system parameters are solved on a COMCOR Ci 5000 analog computer for the characteristic transients of the basic plant and the results compared with a recently proposed LMFBR design. A digital computer automatic control program is developed which uses, in addition to the ideas of derivative and proportional control, precomputed control trajectories. The digital controller design is implemented by applying FORTRAN IV programming to the XDS 9300 digital computer. The effectiveness of the strategy for the automatic controller is demonstrated by using various step changes in the load demand.

A special software routine was written to automatically scale the analog computer and proved to be quite useful in improving the operating efficiency of the hybrid computer simulation.

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